AD

6

AMSMC/RD/MR-7

SIMULATION OF THE STATE OF THE M42/M46 GRENADE DURING PRESS LOADING

GEORGE J. SCHLENKER

DECEMBER 1985

Distribution Statement
Approved for public release; distribution unlimited.

U.S. ARMY ARMAMENT, MUNITIONS AND CHEMICAL COMMAND
READINESS DIRECTORATE
ROCK ISLAND, ILLINOIS 61299-6000

DISPOSITION

Destroy this report when no longer needed. Do not return it to the originator.

DISCLAIMER

AMSMC/RD/MR-7

SIMULATION OF THE STATE OF THE M42/M46 GRENADE DURING PRESS LOADING

George J. Schlenker

December 1985

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AMSMC/RD/MR-7	2. GOVT ACCESSION NO. AD-A163 234	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Simulation of the State of the M42/M46 Grenade During Press Loading		5. TYPE OF REPORT & PERIOD COVERED Report - Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George J. Schlenker		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Armament, Munitions and Chemical Command Readiness Directorate Rock Island, IL 61299-6000		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE December 1985
		13. NUMBER OF PAGES 64
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLAS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Additions to/from the DISTRIBUTION LIST are invited and should be forwarded to the following address: Commander, US Army Armament, Munitions and Chemical Command, ATTN: AMSMC-RDA-S, Rock Island, IL 61299-6000 AUTOVON 793-5041/6370

18. SUPPLEMENTARY NOTES

f, i.k

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Operations Research,	Explosive Incidents
Continuous Simulation	Energetic Materials
Industrial Operations,	Pressed Composition A-5,
Press Loading	Numerical Methods

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a contribution to an ongoing study of explosive incidents (blows) which occur during press loading of the M42/M46 grenade. One of the causal mechanisms posited for the blows is brittle fracture of the grenade body. The physical state of the grenade during final consolidation is of critical importance for this mechanism. A detailed simulation of the compression phase of final loading helps to verify the feasibility of this causal mechanism and to suggest means of minimizing a part of the rate of incidents. This report

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Block 20 (Continued)

describes a continuous simulation of several, related phenomena which occur during final consolidation. These phenomena include: (a) compaction of the bulk HE, (b) production of elastic strain in the grenade body, (c) elastic compression of RDX particles in the HE, (d) kinematics of the punch, (e) heating of the HE, and (f) diffusion of heat within the grenade. A sample of simulation results is given in graphical form, with key variables displayed as functions of punch displacement and of time. Sensitivity of results to certain parameters is shown. Comparisons are made between some experimental measurements and results of the simulation. These comparisons demonstrate the validity of the simulation within the limits imposed by its scope. For the interested analyst, the implementing computer program is listed and explained.

EXECUTIVE SUMMARY

This report is a contribution to an ongoing study of explosive incidents (blows) which occur during press loading of the M42/M46 grenade. High explosive (HE) Composition A-5 is pressed into a steel body (either M42 or M46) of the grenade in two operations: pre- and final -consolidation. The latter is nearly always where blows occur. Several causal physical mechanisms for blows have been hypothesized. One of these mechanisms involves brittle fracture of the grenade body. If a crack opens and propagates, the rapid release of elastic strain energy at the interface of the body wall and HE fill appears to be capable of igniting the HE. The physical states of the grenade body and of the HE during the compaction phase of final consolidation are critical to this mechanism. Quantification of these states helps to verify the feasibility of the brittle-fracture mechanism and to suggest means of minimizing the portion of the blow rate contributed by this mechanism. This report describes a continuous simulation of several, related physical processes which occur during the final consolidation of the HE in the M42/M46 grenade. Typical simulation results are presented in graphical form, with pertinent variables displayed as functions of both punch displacement and time. The sensitivity of these results to certain parameters is shown. For example, punch travel and work done by the punch are shown to be sensitive to the initial, preconsolidated system state. Also the max hoop stress and hoop strain energy are sensitive to peak punch pressure. Where possible, comparisons are made between experimental data and results of the simulation. These comparisons demonstrate the validity of the simulation within the limits imposed by its scope. For the interested analyst, the implementing computer program is listed and explained.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

AMSMC-RDA-S December 1985

MEMORANDUM REPORT

SUBJECT: Simulation of the State of the M42/M46 Grenade During Press Loading

1. Foreword

Order of topics in this report represents increasing detail. Background information is presented first to set a context and to motivate the work presented here. The goals of the subject simulation are given next, followed by the scope of- and assumptions for -the simulation. Simulation results are given in tables and graphs, followed by comments about these results. Sections on validation and methodology complete the body of the report. A source program listing of the simulation is given in Annex A. Annex B contains a memorandum concerning a model of the bulk density of Comp A-5. The following references are cited thruout the report.

2. References

a. MFR, AMSMC-RDA-S, 22 Oct 85, subject: Evidence for a Steel-Supplier Effect on the Rate of Press Blows in M42 and XM77 Grenades.

b. Technical Report ARLCD-TR-79002, Collett, R.W. and England J.T., ARRADCOM, LCWSL, Dover, NJ, Jun 79, title: Press Loading Incident Investigation of M42/M46 Grenade Bodies.

c. MFR, AMSMC-RDA-S, 9 Aug 85, subject: Some Observations About the Explosive Sensitivity of Comp A-5.

d. MFR, AMSMC-RDA-S, 28 Aug 85 (Revised 24 Sep 85), subject: Predicted Bulk Densities of Comp A-5 and Comp A-4 as Functions of Peak Consolidation Pressure. (Given in Annex B.)

e. Technical Report #371, 23 Aug 85, Day & Zimmerman Kansas Div., subject: Investigation of Effects of Charge Density on Penetration in M42/M46 Grenades.

f. MFR, DRSMC-SAS (R), 4 Nov 83, subject: Particle-Size Distribution of Nominal Class 1 RDX Before Incorporation and After Extraction From Extrusions of Comp C-4.

g. Reference Book, Kaye, S.M., US ARDC, Dover, NJ, c. 1980, title: Encyclopedia of Explosives and Related Items, Vol 9.

h. Text Book, Timoshenko and Goodier, McGraw-Hill, NY, c. 1951, title: Theory of Elasticity.

i. MFR, AMSMC-RDA-S, 23 Aug 85, subject: Time Series Analysis of the Peak Consolidation Load for Pressing of HE into M42/M46 Grenades.

3. Background

Previous studies of explosive incidents during press loading of M42/M46 grenades posited various physical mechanisms for initiating an explosion. Ref 2a presents arguments supporting the mechanism of brittle fracture of the grenade body. The scenario for an explosion with this mechanism is as follows: During final consolidation of the HE (Comp A-5), a latent crack suddenly opens and propagates. A rapid release of elastic strain energy in the grenade body is deposited at the surface of the HE in proximity to the crack. This energy release over a small area is regarded as sufficient to initiate an explosion of the HE *. If this mechanism is responsible for some of the incidents, one would expect to see the observed variation in blow rate between bodies by different body producers, since variation in metal parts quality between producers is quite evident. Ref 2b also presents evidence for a steel-supplier effect, which, again, is germane to the mechanism of brittle fracture. A similar phenomenon, occurring in the powder nest, is one of the mechanisms hypothesized in Ref 2b. The very limited set of experiments reported in Ref 2b failed to demonstrate a blow with either a cracked body or a cracked nest. However, these negative results are not persuasive, because only rare and special conditions--very rapid energy deposit in a small area--must exist in order to provoke a blow. Based on simulated results, brittle fracture must still be considered a credible mechanism.

4. Considering this mechanism, several actions to reduce the frequency of press blows are appropriate: (a) Improve the specified quality, including fracture toughness, of steel used in making grenade bodies. This action is suggested in Ref 2a. (b) Improve quality of grenade bodies from the "marginal" body producers. Actions started by AMCCOM Quality Assurance in 1985 address this issue. (c) Use a less sensitive HE fill, such as Comp A-4. This idea is still on the back burner. (d) Load at a lower peak consolidation pressure. This suggestion is made in Ref 2c, and justified by data which show reduced explosive sensitivity when grain breakage is minimized. Altho easy to implement, the last suggestion has met resistance on the grounds that effectiveness (penetration & lethal area) would suffer. Nevertheless, some tradeoff here seems possible to reduce blow rates.

5. Because of the importance of the state of stress of the grenade body to the brittle fracture mechanism, some effort was made to take experimental measurements (for example, Ref 2b). And, because of the importance of HE density to grenade performance, various data have been gathered relating HE density to peak consolidation load (or pressure), under both quasi-static (very slow rate of loading) and transient conditions (which occur in load plants). Some of these experimental results are compared with simple mathematical models in Ref 2d. Ref 2e presents additional results for the transient loading condition, in a study designed to relate average HE density to grenade penetration performance. Notwithstanding these experiments to understand the processes occurring during press loading, to my knowledge no unified mathematical model has been developed to simulate the physical processes which interact during final consolidation. This memorandum presents such a model. Tho the simulation is not very sophisticated, model output is in good agreement with pertinent experimental data.

* Ref 2g indicates that the threshold value of energy per unit area for shock ignition of RDX is about 10 cal/sq cm, a value which may be achieved by release of elastic strain energy in the body.

6. Goals of the Simulation

The primary goal of the simulation is to achieve better understanding of the relationship of several physical parameters pertinent to loading of the M42/M46 grenade. Understandings of this sort ultimately guide design of experiments and help to quantify improvement in rate of press blows, expected to accompany loading at lower peak pressure. A partial list of questions addressed by the simulation may clarify my intentions:

(a) How does the HE respond to punch displacement during consolidation? For example, how does punch load vary with punch displacement and with time? (In this case, time is simply a convenient variable for use in comparison with experimental results. Since punch acceleration is quite low, inertial forces are not important. The phenomena are mostly kinematic rather than dynamic.)

(b) How does the work done by the punch vary as a function of punch displacement and as a function of time?

(c) What portion of the punch work is invested in elastic, i.e., recoverable, energy components? This question has a bearing on volume change in the HE following punch withdrawl. Also, these elastic strain-energy components would become sources of energy for initiating an explosion of the HE, if a metal failure occurred during compression.

(d) Are physically significant temperature gradients developed within the RDX particles during consolidation?

(e) Do any of the variables of interest display a large sensitivity to the initial conditions for final consolidation, i.e., does variation in preconsolidation affect final results?

(f) How well does the model match the experimental load-versus-time data?

It is beyond the scope of this model to address issues such as:

(a) Specifically, what happens if a brittle fracture of a grenade body occurs during consolidation?

(b) What stress concentrations occur in various regions of the body?

(c) Where does RDX grain fracture occur during loading, and what is its extent?

(d) What is the nature of the flow in the HE during consolidation?

7. Scope and Assumptions

In terms of fidelity to geometric details of the grenade body, the model is quite crude. For the purpose of calculating hoop stress and hoop strain in the body, the grenade is modeled as a regular cylindrical sleeve, supported on one end by a smooth, unyielding surface. The HE configuration is assumed to have cylindrical symmetry within the cavity. The simulation model is descriptive; it uses semiempirical results where appropriate, and does not insist on starting from first principles. In spite of evidence of RDX grain fracture, cited in Refs 2c and 2f, the model ignores this phenomenon. Further, because of its simple geometry, no attempt is made to describe the actual flow of the HE with respect to the punch and body cavity in an actual M42/M46 grenade. However, the effects of a pressure gradient within the HE are considered. Most of the mechanical and thermal material characteristics were obtained from standard references such as Ref 2g. The compaction model (avg HE density versus peak pressure) uses the functional form described in Annex B. This model assumes a constant pressure gradient within the HE. The pressure decreases linearly from a maximum value of pmax, at the punch face, to a minimum value of a constant, g, times pmax. The value of g used here (0.6) is obtained from data in Ref 2e. The assumed constant pressure gradient within the HE is also used in deriving an expression for the RDX elastic strain energy. Hoop stress in the simulated grenade body is calculated using the Lame equation for thick-walled cylinders (Ref 2h). A formula for body strain energy is derived from the last equation, which assumes elastic behavior.

8. Results of the Simulation

The loading simulation is implemented by a computer program COMPACT. A source listing of this program, in Simscript 2.5, is located in Annex A. The logic of this program is sketched below (p. 19, Methodology). A portion of the output from COMPACT is shown in Table 1. After echoing the input parameters, the state variables, which characterize the HE and the grenade body, are printed as functions of the displacement of the punch. The initial, average density of the HE is chosen by the program user. This value suffices to initialize the simulation for the final consolidation cycle. Punch displacement and cycle time are taken as zero at this point. Time is calculated from punch displacement, since these are kinematically related by the punch cam shape and operational speed of the press. Program variables are plotted as functions of punch travel and time. These are shown in Figures 1 thru 19, on pages 7 thru 16. Results are discussed in paragraph 10, page 17.

9. Parametric Analyses

Two simulated body dimensions were treated as parameters for sensitivity analysis: (a) the thickness of the wall of the sleeve, representing the grenade body, and (b) the effective length of the sleeve which is exposed to internal pressure. The last parameter is determined by shape of the punch and by the 1-D nature of body stress calculations. Three values of wall thickness -- 0.110 inch, 0.115 inch, and 0.120 inch -- are used at a effective body length of 1.4 inch. And, two values of the body length -- 1.0 inch and 1.4 inch --are used with a nominal wall thickness of 0.115 inch. Results are shown in Tables 2 and 3. In each case the initial punch pressure is 5.1 kpsi and the final pressure is 25 kpsi (to terminate the comression phase). The initial pressure corresponds to an average HE density of 1.44 g/cc. Since the final state is prescribed, certain variables, such as punch work and loading time, are not very sensitive to the parameters. However, variables such as hoop strain energy, are. Sensitivity to the initial state of compression is shown in Table 4. Sensitivity to the final state of compression is shown in Table 5.

TABLE 1. SAMPLE OUTPUT FROM THE COMPUTER PROGRAM: COMPACT

DIMENSIONS OF CYLINDRICAL SLEEVE SIMULATING THE GRENADE BODY

INTERNAL DIAMETER ___	3.2004	CM ___	1.2600	INCH
OUTSIDE DIAMETER ___	3.8100	CM ___	1.5000	INCH
EFFECTIVE HEIGHT ___	3.5560	CM ___	1.4000	INCH
PUNCH TRAVEL LIMIT ___	0.4157	CM ___	0.1637	INCH

PROPERTIES OF RDX , USED IN THE EXPLOSIVE FILL:

DIAMETER OF RDX PARTICLE ______	160.0	MICRON
RADIAL GRID ELEMENT OF RDX ______	8.0	MICRON
SPECIFIC SURFACE OF RDX ______	206.0	SQ CM/G
THEORETICAL MAX DENSITY OF RDX _	1.820	G/CC
SPECIFIC HEAT OF RDX ______	0.300	CAL/G/DEG K
THERMAL CONDUCTIVITY OF RDX ___	+7.00000E-04	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF RDX ___	+1.28205E-03	SQ CM/S
YOUNG'S CONSTANT FOR RDX ______	+1.80000E+10	PASCAL
POISSON'S RATIO FOR RDX ______	+2.20000E-01	
BULK MODULUS FOR RDX ______	+1.07143E+10	PASCAL
MASS FRACTION OF RDX IN HE ____	0.985	

THERMAL PROPERTIES OF GRENADE MATERIALS:

RADIAL GRID ELEMENT OF HE ____	+8.00100E-02	CM
TMD OF HE ______	+1.78917E+00	G/CC
SPECIFIC HEAT OF HE ______	+3.01485E-01	CAL/G/DEG K
THERMAL CONDUCTIVITY OF HE ___	+6.95200E-04	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF HE ___	+1.28882E-03	SQ CM/S
RADIAL GRID ELEMENT OF STEEL _	+7.62000E-02	CM
TMD OF STEEL ______	+7.87000E+00	G/CC
SPECIFIC HEAT OF STEEL ______	+1.25000E-01	CAL/G/DEG K
THERMAL CONDUCTIVITY OF STEEL _	+1.65000E-01	CAL/CM/S/DEG K
THERMAL DIFFUSIVITY OF STEEL _	+1.67726E-01	SQ CM/S

INITIAL CONDITIONS AT START OF FINAL CONSOLIDATION:

HE DENSITY ______	1.44000	G/CC		
PRESSURE ON HE ______	5.1046	KPSI ___	35.195	MPA
HEIGHT OF HE COLUMN _	2.58468	CM		
MAX BODY HOOP STRESS _	29.474	KPSI ___	203.21	MPA
HOOP STRAIN IN BODY _	+9.82452E-04			
HOOP STRAIN ENERGY ___	1.1795	JOULE ___	0.2819	CAL
RDX ELASTIC ENERGY ___	0.4880	JOULE ___	0.1166	CAL
CUM WORK BY PUNCH ___	1.6675	JOULE ___	0.3985	CAL

SIMULATED CONDITIONS DURING HE CONSOLIDATION

PUNCH DISPL (CM)	HE DENS (G/CC)	HE PRESS (KPSI)	MAX STRESS (KPSI)	HOOP STRAIN (MU/U)	H STRN ENERGY (CAL)	PUNCH WORK (CAL)	THERM WORK (CAL)	TEMP RISE (D K)	CYCLE TIME (MS)
0.0010	1.4406	5.115	29.53	984.5	0.283	0.467	0.067	0.007	2.75

TABLE 2. SENSITIVITY OF SIMULATION OUTPUT TO BODY WALL THICKNESS

Output Variable	Body Wall Thickness (inch) 0.110	0.115	0.120
Loading Time (ms)	266	268	269
Punch Travel (mm)	3.976	4.031	4.087
Punch Work (cal)	57.5	57.3	57.1
Max Hoop Stress (kpsi)	159.1	151.8	144.9
Hoop Strain Energy (cal)	7.765	7.724	6.815

TABLE 3. SENSITIVITY OF SIMULATION OUTPUT TO EFFECTIVE BODY LENGTH

Output Variable	Effective Length of Body (inch) 1.0	1.4
Loading Time (ms)	268	268
Punch Travel (mm)	4.031	4.031
Punch Work (cal)	57.3	57.3
Max Hoop Stress (kpsi)	151.8	151.8
Hoop Strain Energy (cal)	5.196	7.274

TABLE 4. SENSITIVITY OF SIMULATION OUTPUT TO INITIAL SYSTEM STATE
Internal Diameter (cm) 3.226 Effective Length (cm) 3.556

Output Variable	Initial Punch Pressure/HE Density 4.75/1.42	(kpsi)/(g/cc)	5.10/1.44
Loading Time (ms)	281		268
Punch Travel (mm)	4.392		4.031
Punch Work (cal)	59.6		57.3
Max Hoop Stress (kpsi)	151.8		151.8
Hoop Strain Energy (cal)	7.27		7.27
Remain Heat Energy (cal)	49.5		47.2

TABLE 5. SENSITIVITY OF SIMULATION OUTPUT TO PEAK PUNCH PRESSURE

Output Variable	Peak Punch Pressure 25 (kpsi)	20 (kpsi)	Percent Decrease
Max HE Density (g/cc)	1.697	1.678	1.1 %
Final HE Density (g/cc)	1.676	1.661	0.9 %
Max Hoop Stress (kpsi)	144.8	115.8	20.0 %
Hoop Strain Energy (cal)	6.80	4.35	36.0 %

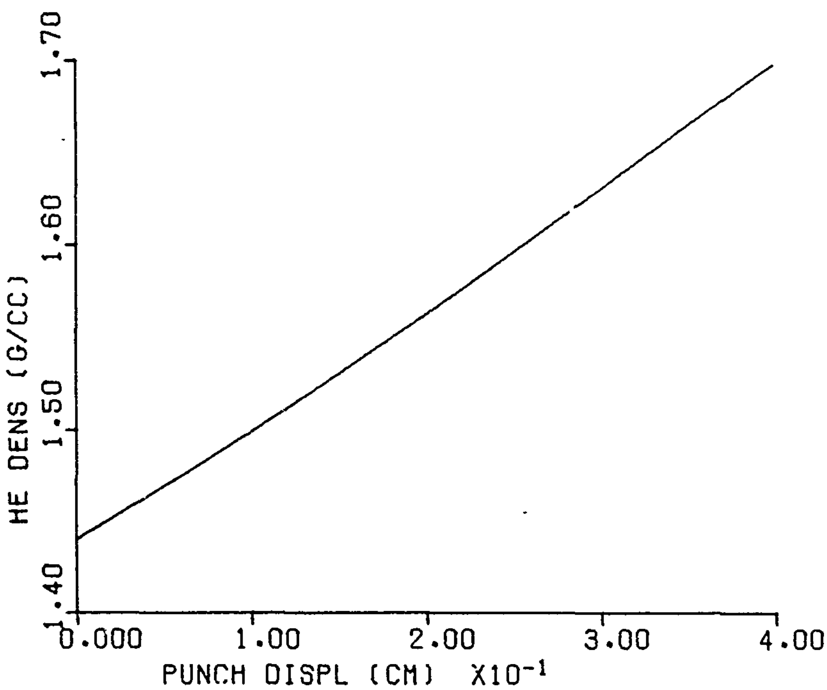

Figure 1. Avg Density of HE as a Function of Punch Displacement

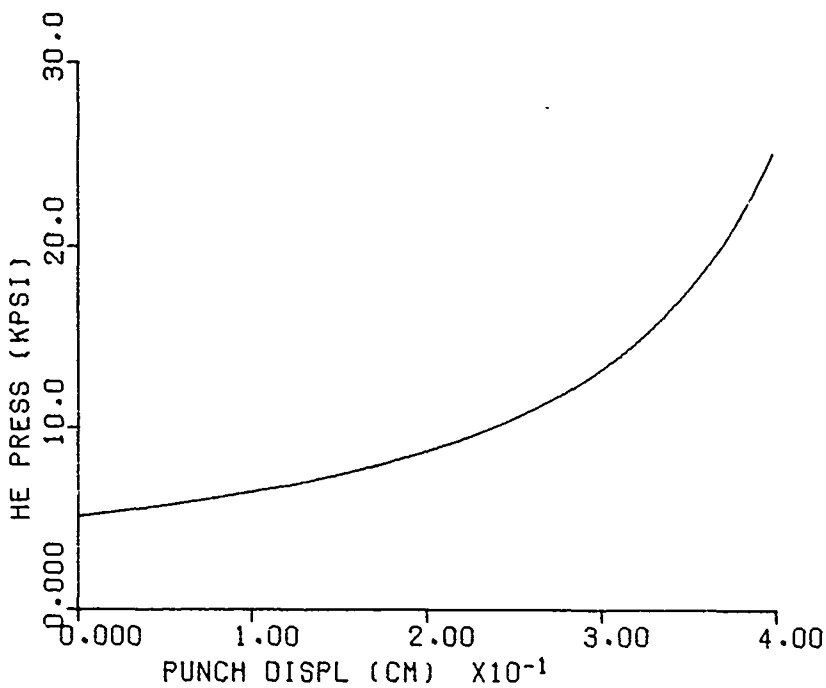

Figure 2. Max Pressure on the HE Versus Punch Displacement

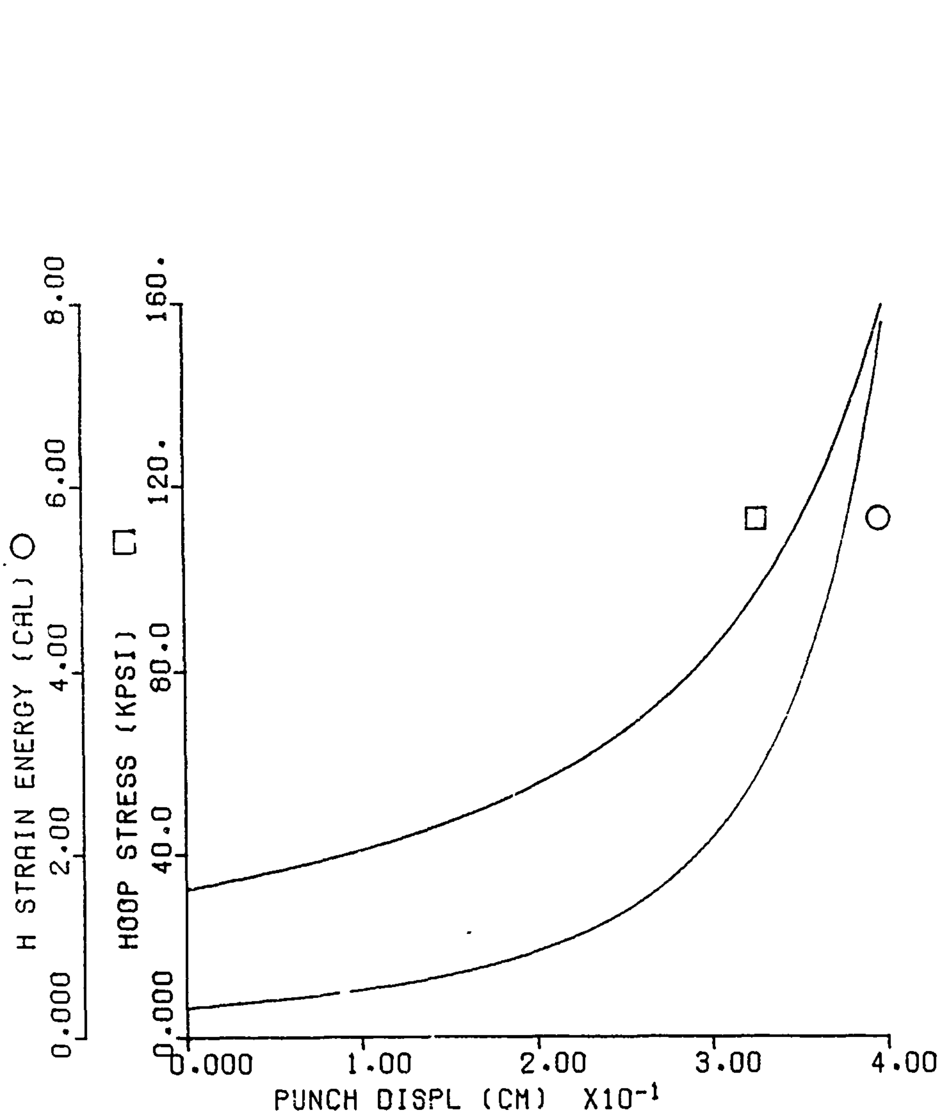

Figure 3. Hoop Strain Energy and Max Hoop Stress in the Grenade Body Versus Punch Displacement

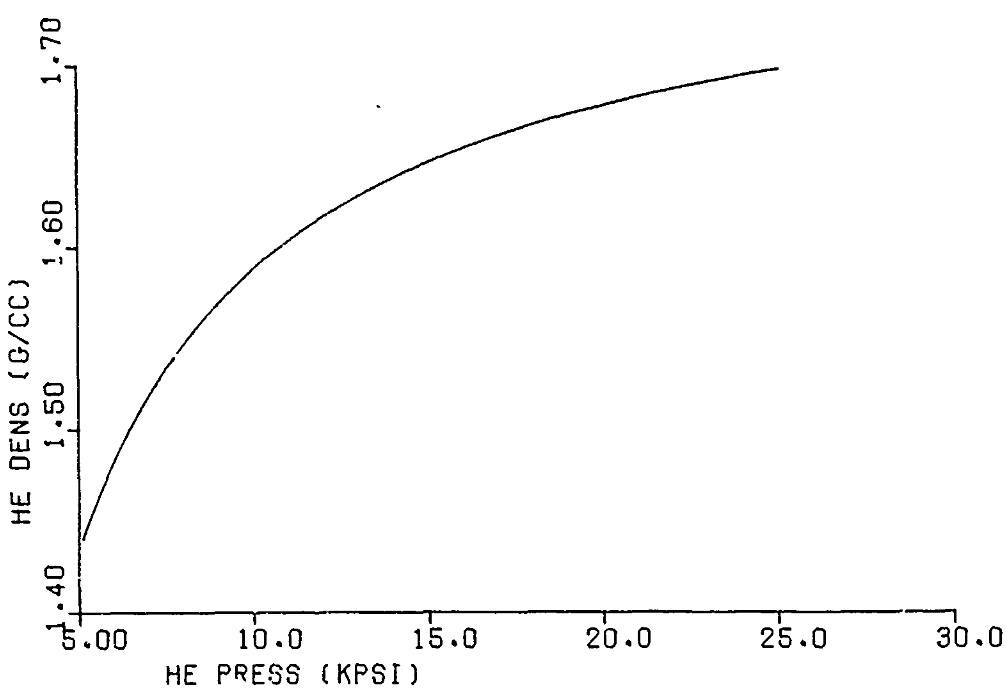

Figure 4. Avg Density of the HE Versus Max HE Pressure

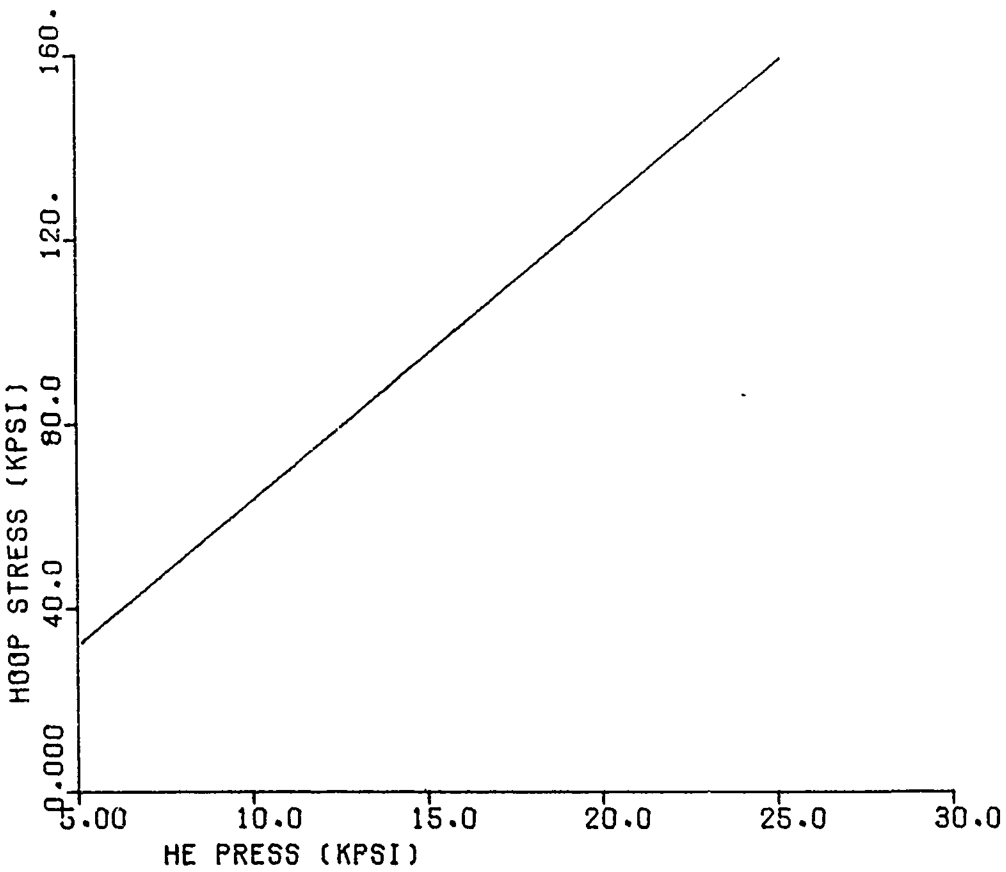

Figure 5. Max Hoop Stress in Grenade Body Versus Max HE Pressure

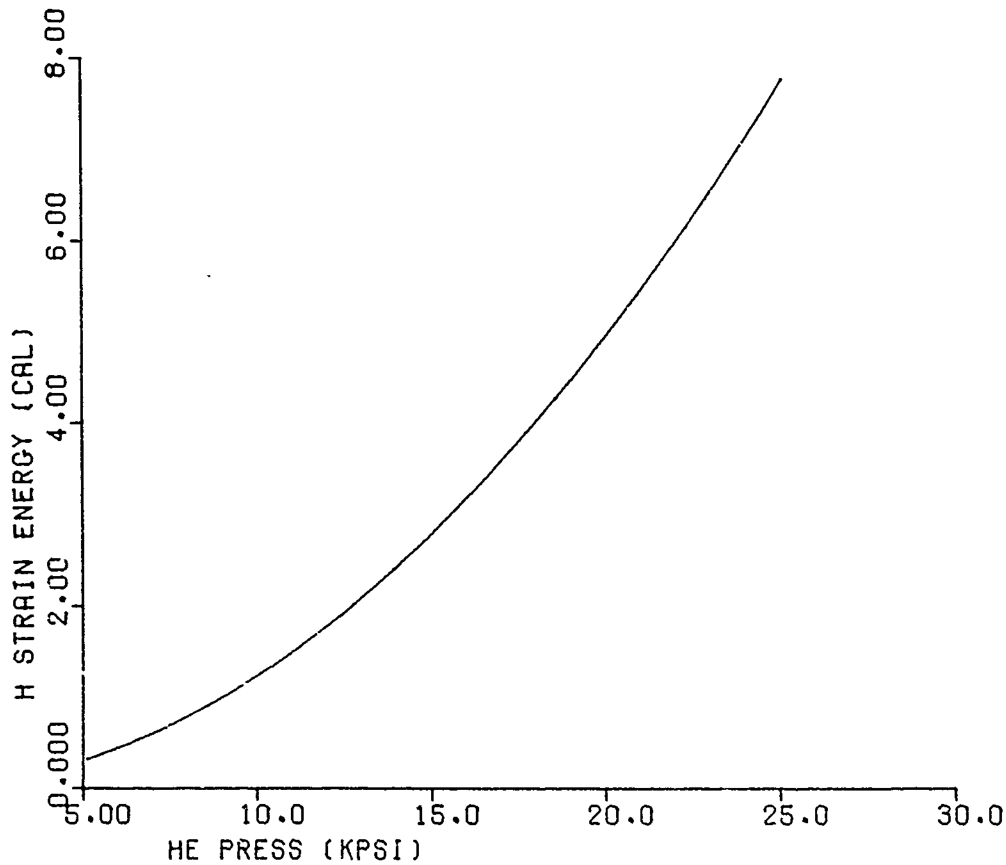

Figure 6. Hoop Strain Energy in the Grenade Body Versus Max HE Pressure

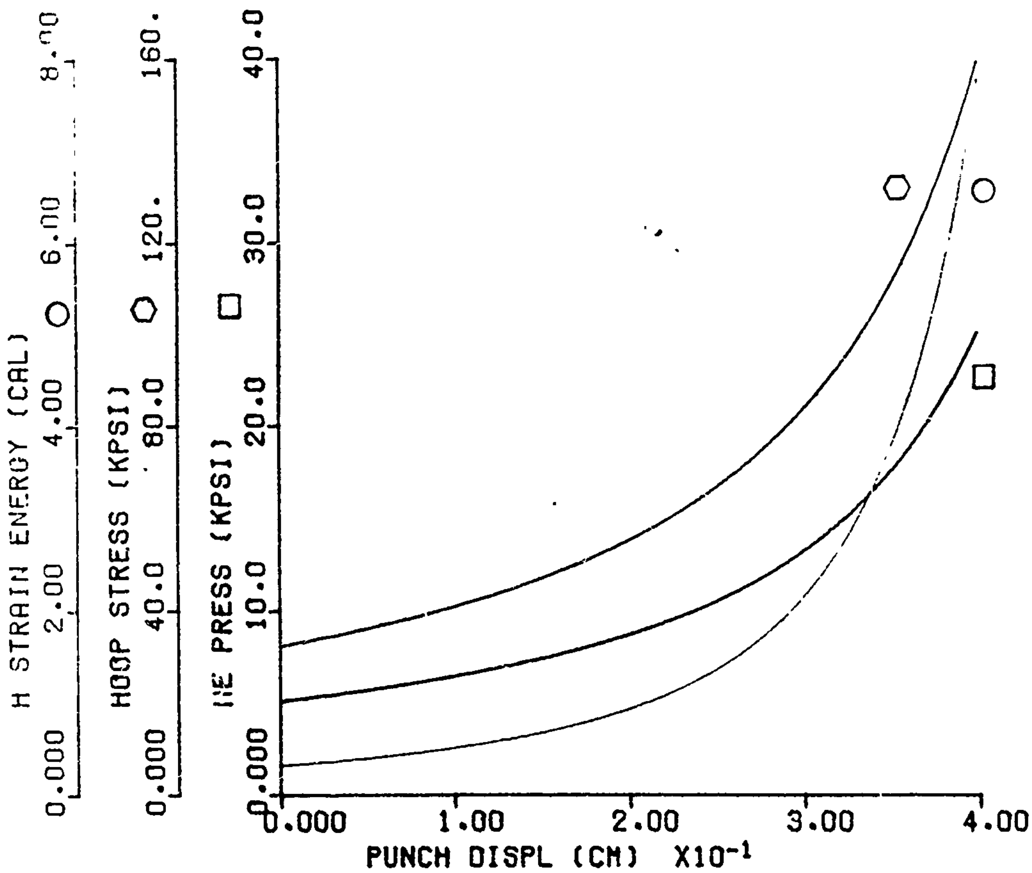

Figure 7. Comparison of Several Variables as Functions of Punch Displacement

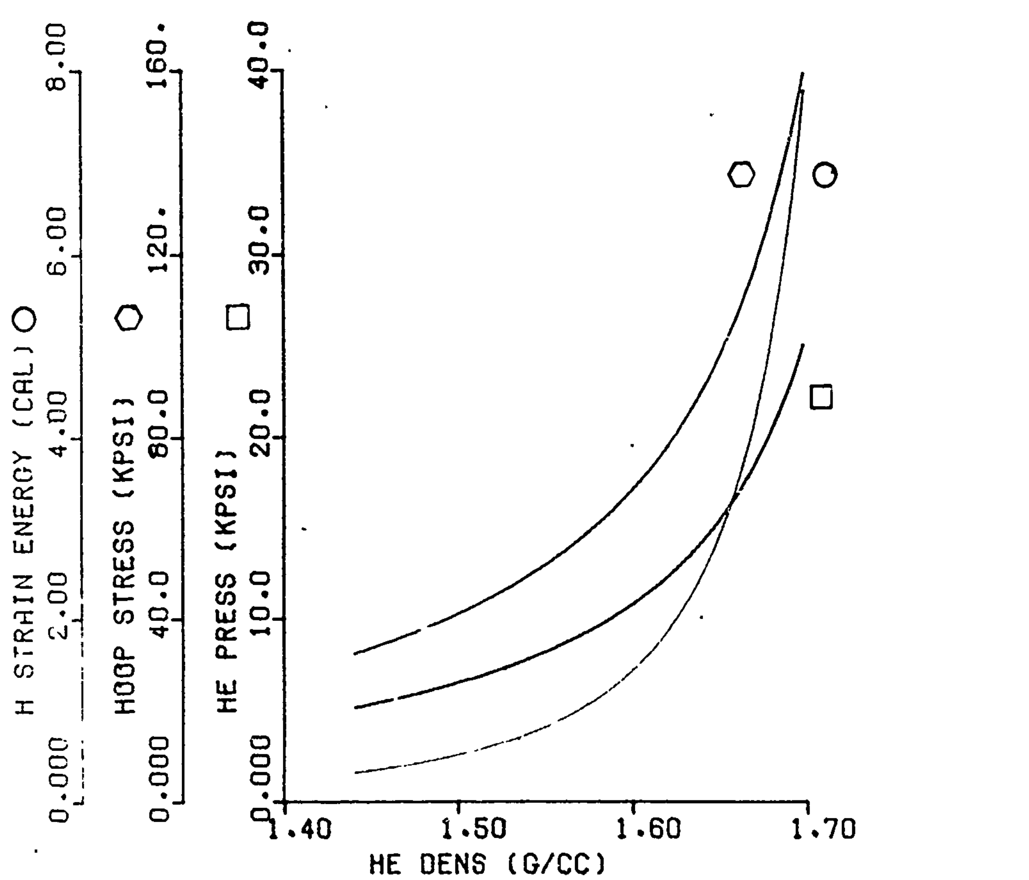

Figure 8. Comparison of Several Variables Versus Avg HE Density

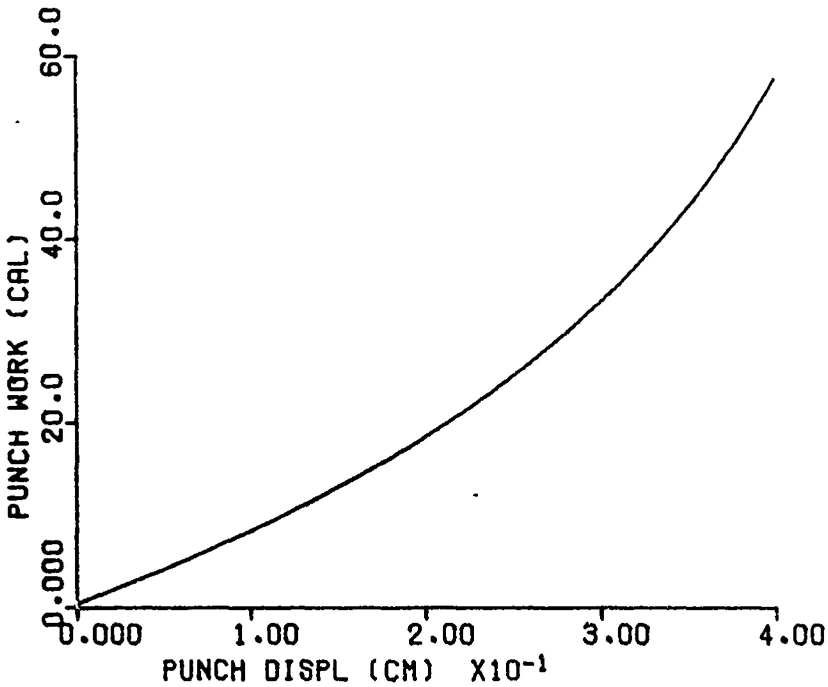

Figure 9. Work Done by the Punch as a Function of Punch Displacement

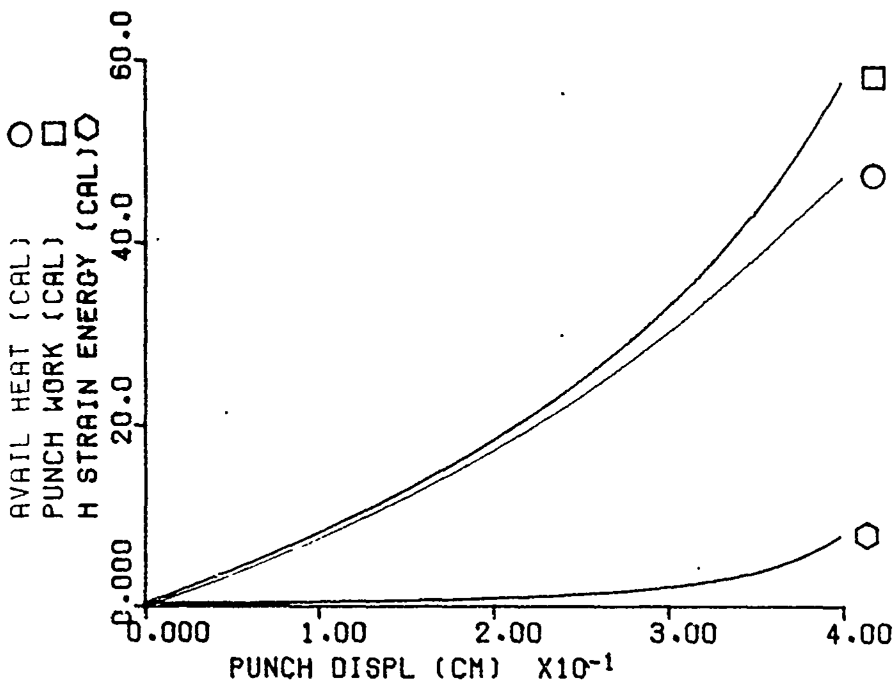

Figure 10. Comparison of Energy Components as Functions of Punch Displacement

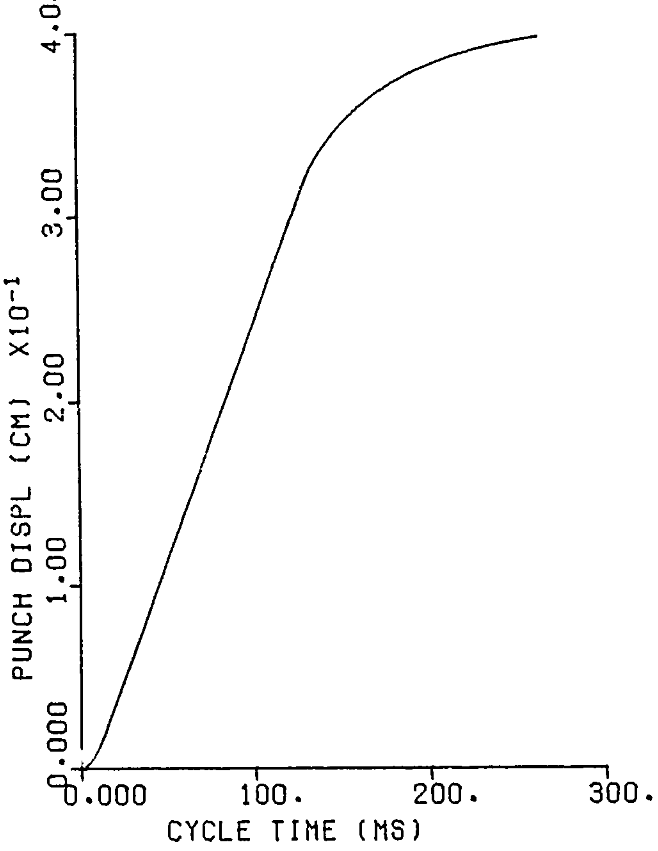

Figure 11. Punch Displacement Versus Cycle Time

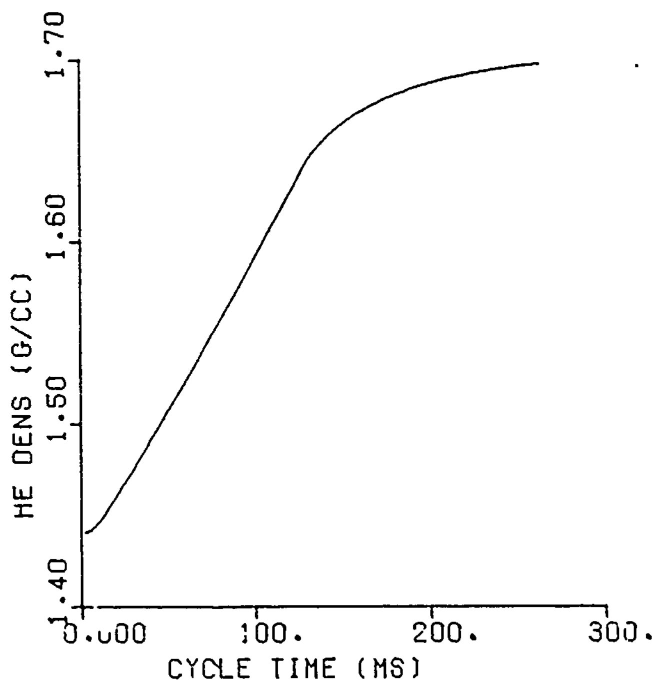

Figure 12. Avg Density of the HE Versus Cycle Time

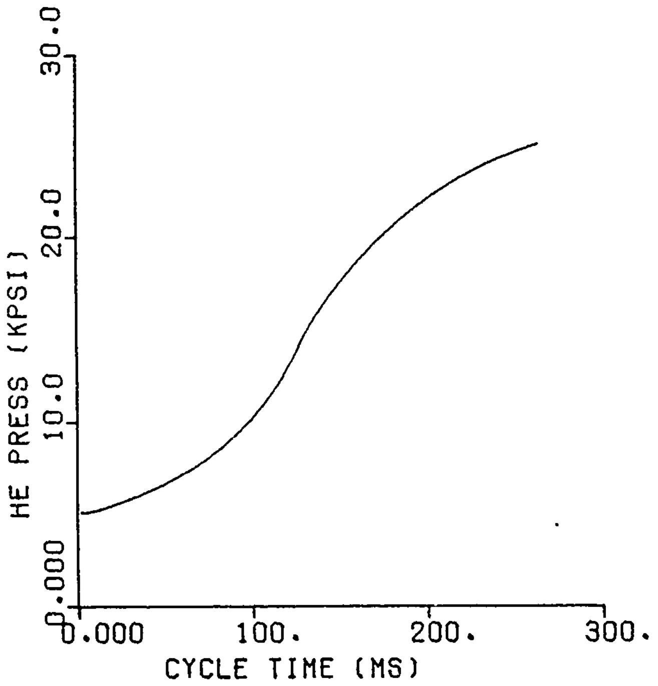

Figure 13. Max HE Pressure Versus Cycle Time

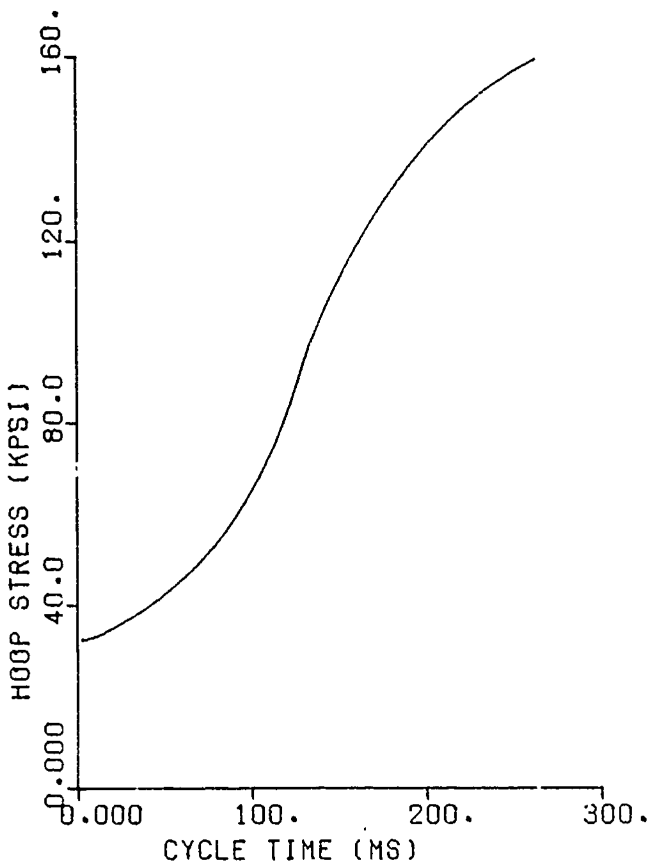

Figure 14. Max Hoop Stress Versus Cycle Time

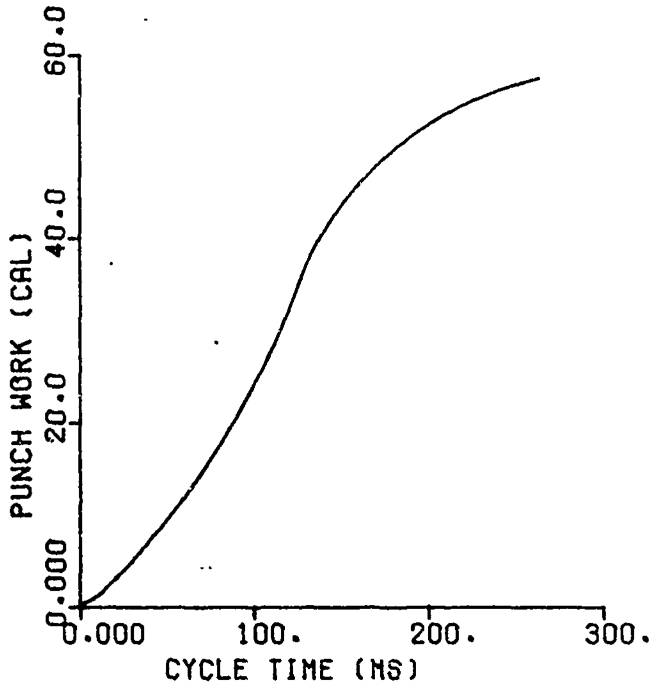

Figure 15. Punch Work Versus Cycle Time

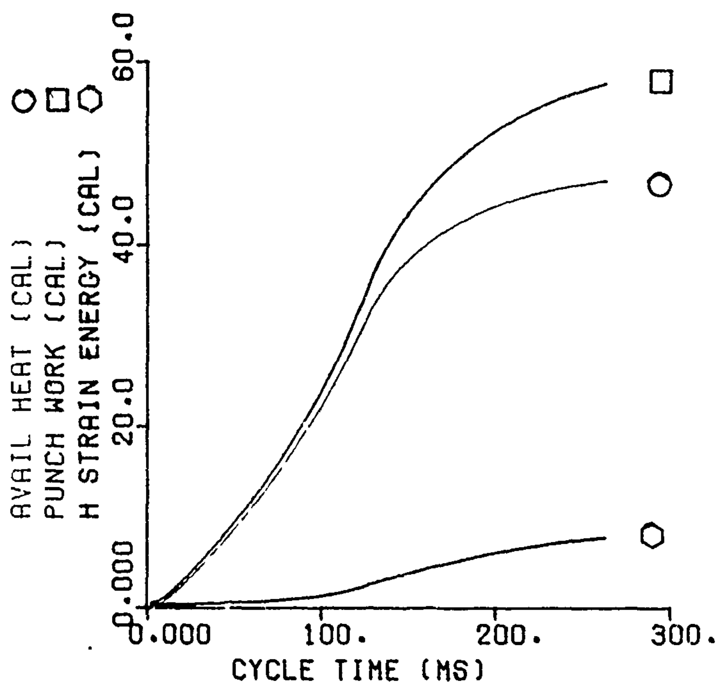

Figure 16. Comparison of Energy Components as Functions of Cycle Time

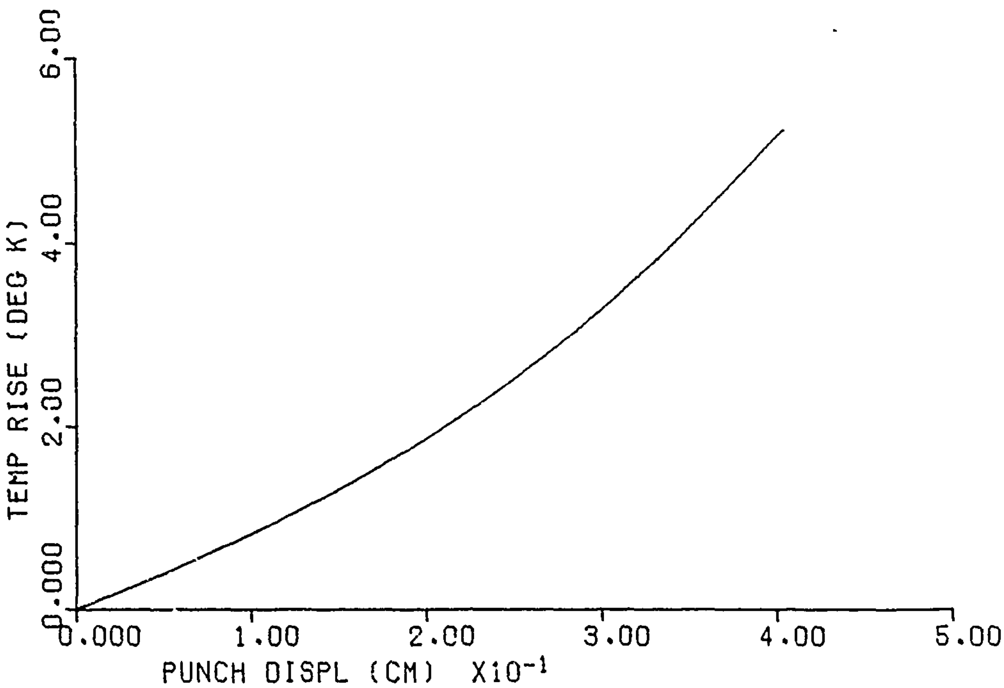

Figure 17. Avg HE Temperature Rise as a Function of Punch Displacement

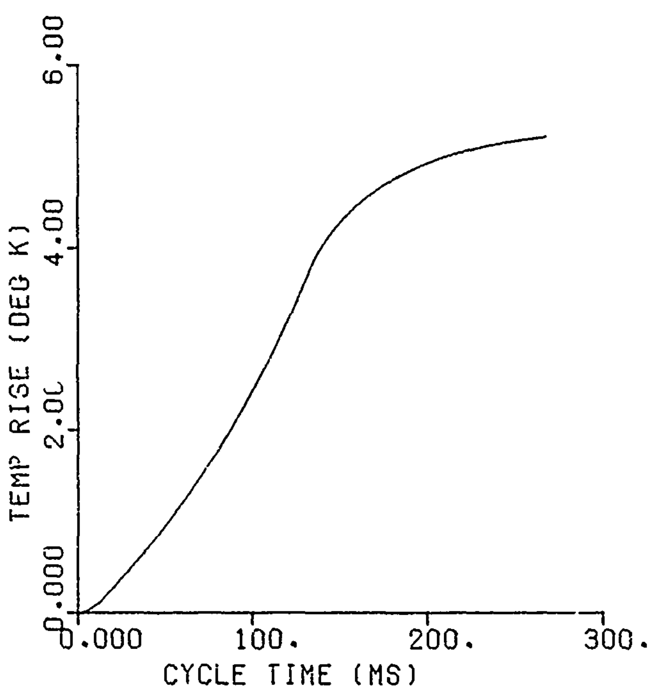

Figure 18. Avg HE Temperature Rise as a Function of Cycle Time

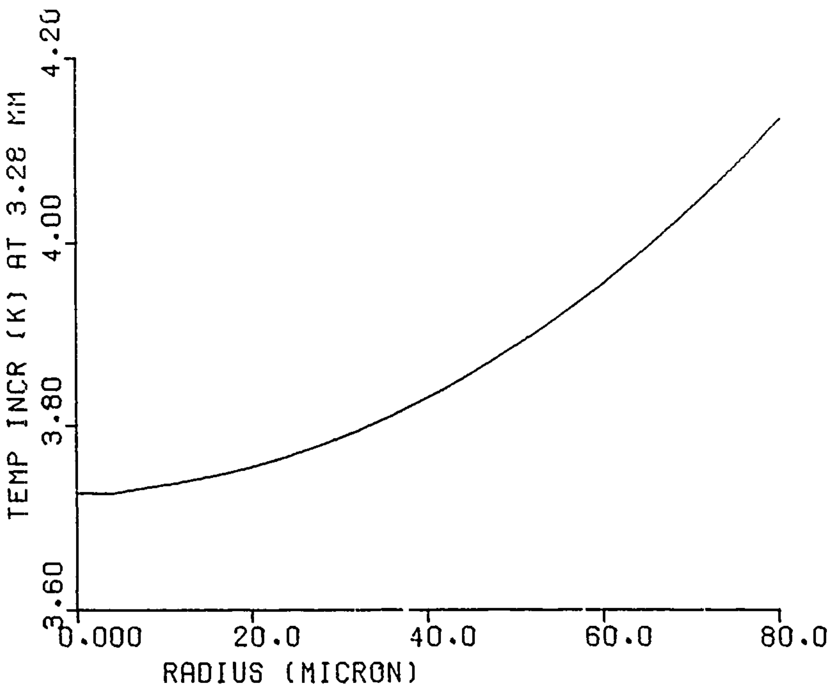

Figure 19. Radial Profile of Temperature in an RDX Particle (at 3.28mm Punch Travel)

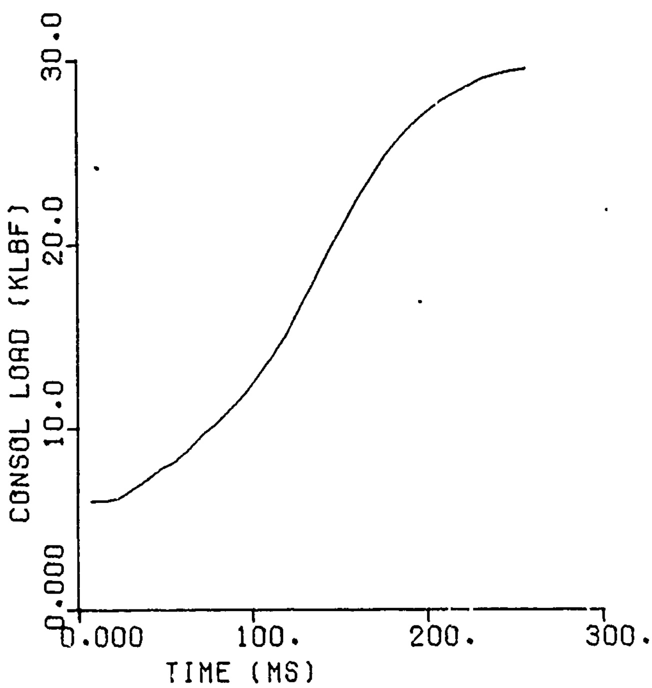

Figure 20. Experimental Consolidation Load Versus Cycle Time

10. Discussion of Results

For the most part the graphical results do not require comment. In some cases, however, my observations may help to clarify an issue or to make an interpretation. The first ten figures show important variables as functions of punch displacement (or travel), whereas the last ten are largely functions of cycle time. By "cycle time" is meant time, measured from the start of the compression phase of the final consolidation cycle. Another semantic point: Maximum pressure on the HE fill is identical to the punch pressure. These terms are used interchangeably. In Figure 1 the average density of the HE is shown plotted as a function of punch displacement. Altho this relationship appears linear, it is not quite. Departure from linearity is due to progressive hoop strain in the body wall as the punch advances. Figure 2 shows the punch pressure as a function of punch travel. It is clear that the most rapid increase in pressure happens during the final half of the forward displacement. This functional form indicates that the HE behaves compressionally as a very nonlinear spring. Hoop strain energy and maximum hoop stress in the grenade body are shown as functions of punch displacement in Figure 3. It is noted that strain energy is a quadratic function of stress. Also observe that hoop stress builds rapidly near the end of forward travel of the punch. For these reasons the hoop strain energy in the body is strongly dependent upon punch travel during the last quarter of the forward stroke. Therefore, one expects that brittle fracture would most probably occur in the last quarter of compressional punch travel. Only in this last quarter does the body strain energy exceed about two calories. Note that the max strain energy is nearly 8 calories. Figure 4 is a cross-plot of avg HE density versus punch pressure. It is apparent that at about 15 kpsi pressure, the rate of increase of HE density diminishes rapidly. Max body hoop stress is shown as a function of punch pressure in Figure 5. Maximum hoop stress occurs at the inside surface of the body wall. As predicted by this model, max hoop stress is a linear function of punch pressure. Figure 6 shows the hoop strain energy in the grenade body as a function of punch pressure. When plotted in this manner, hoop strain energy exhibits a more uniform rate of increase than when plotted versus punch displacement, as in Figure 3. In both Figures 7 and 8, hoop strain energy, max hoop stress, and max HE pressure are compared functionally. Whether the abscissa is punch travel (Fig 7) or avg HE density (Fig 8), it is seen that strain energy shows the greatest relative variation of these variables. Hoop stress and punch pressure exhibit more uniform growth. Figure 9 shows work done by the punch as a function of punch displacement. Because of the greater stiffness of the HE fill near the end of forward travel of the punch, the rate of work done by the punch increases progressively. This work is converted into both elastic and inelastic energy components. The elastic components are: (a) hoop strain energy in the grenade body, and (b) bulk-compression strain energy of RDX crystals in the HE. Punch work, available heat, and hoop strain energy are shown as functions of punch travel in Figure 10. The work performed by the punch is the total available energy. This is divided among the components: (a) body hoop strain energy, (b) RDX strain energy, (c) thermal loss, and (d) available thermal energy. Of these components, only the largest two are shown here.

THIS

PAGE

IS

MISSING

IN

ORIGINAL

DOCUMENT

predicted rise in HE temperature, when loading to 26.4 kpsi, is 5.2 deg K. This compares with a measured value of 3.9 deg K, when loading to the same point (max load of 33 klbf) *. A max external hoop stress is reported (Ref 2b) as 105.5 kpsi for a peak punch load of 26.5 klbf. Simulated external stresses were obtained for the same max compression (21.2 kpsi) for two values of body ** wall thickness. For a 0.12-inch wall, the predicted peak, external hoop stress is about 102 kpsi; whereas, for a 0.11-inch wall, this value is about 107 kpsi. Agreement between the simulated and measured values of these variables is surprisingly close. With respect to the third variable used for comparison, one should note that functions, not scalars, are being compared. A single, arbitrary parameter in the simulation--max punch speed--is selected to obtain a good match of theory and experiment. This parameter adjusts the kinematics of the simulation to that of the experiment; however, this parameter does not affect the shape or the amplitude of the load function. Therefore, good agreement in the simulated and measured load functions constitutes a challenging test of the validity of the model. The experimental load-time curve, shown in Figure 1 in Ref 2i, is matched by simulated results well within experimental error (+ or - 1.6 klbf) over the loading interval of about 260 ms from start of cycle. The experimental load function is shown for comparison in Figure 20, for just the compression phase of the load cycle. No systematic difference is apparent between model and measured functions.

13. Methodology

Before discussing math models for various phenomena, I will outline the procedure followed in simulating the loading process. The independent variable in the simulation is the displacement (or travel) of the punch. The kinematics of the process are obtained thru the functional relationship between punch displacement, xp, and punch speed, sp. Only the compression-, or loading, -phase of the consolidation

---

* Temperature in this environment is very difficult to measure. Ref 2b states that two types of transducers were used--theromcouple and nickel-foil gage. The nickel-foil gages were too fragile; three of four were damaged. Two measurements, at different locations within the HE, were made with thermocouples. One measurement was made just above the tip of the punch, with the HE consolidated at at max load of 43 klbf. The reported temperature rise in this case is 18.9 deg K. This value seems much too high; and, in any case, does not represent a volume-average temp rise. The other reported measurement was made between the axis and wall near the top or cap end of the cavity. This is the value (3.9 deg K) cited here, which was obtained at the lowest reported peak load (33 klbf). Parenthetically, one observes that if the temperature variation within the HE is a great as measured, this fact would support the assertion that considerable differential flow and, possibly, grain fracture occurs within the HE.

** Recall that the grenade body is represented by a uniform cylindrical sleeve. Wall thickness of the sleeve is the parameter in this instance. The parametric variation studied (0.010 inch) is about three times the body-to-body standard deviation for a particular body producer.

cycle is simulated. After initialization of the grenade to a given HE density and corresponding punch pressure, the following steps are followed until the desired terminal state is achieved:

(a) The punch is advanced thru a small increment. This increases the density of the HE. (One micrometer is the increment used here.)

(b) The max pressure on the punch and the pressure gradient in the HE are calculated at the current average HE density. The incremental work performed by the punch, to advance incrementally at this pressure, is added to cumulative punch work.

(c) The (one-dimensional) hoop strain in the cylindrical sleeve, which represents the grenade body, is calculated. Max strain is reached at the inside radius. Elastic behavior of the metal is assumed.

(d) Since the hoop strain increases the HE cross-section, calculate the additional displacement of the punch (at this pressure) required to preserve HE density at the value calculated previously with no incremental body strain.

(e) At each movement of the punch, by delxp, add the punch work to the cumulative punch work. The isobaric, incremental work is just the total force times delxp, where the total force is the product of the current values of HE cross-section and punch pressure. Updates of punch work are required at steps (b) and (d).

(f) Since the RDX particles within the HE experience elastic volumetric compression, calculate the strain and the strain energy in the RDX mass.

(g) To obtain the total available heat energy, subtract the sum of hoop-strain energy plus RDX strain energy plus thermal loss to body from the punch work. (All cumulative energy terms are calculated in joules and reported in units of J and calories.)

(h) The total incremental punch displacement (since prior loop pass) has consumed a time increment which is the ratio of the displacement increment to the punch speed. This speed is obtained as a function of current value of xp. Time is updated by addition of the time increment.

(i) The time increment is also used to calculate the thermal flux to the RDX particles. Flux is the incremental heat/total particle surface/time increment. At the program user's option, the temperature distribution as a function of RDX particle radius is obtained by numerically solving the diffusion equation, using the average thermal flux as the outside boundary condition.

(j) The heat generated incrementally during this loop pass is used to calculate the volume-average temperature rise of the HE, by dividing by the heat capacity of the HE. HE temperature is updated by this increment.

(k) The incremental heat loss from the HE to steel body is calculated using current average values of HE temperature and steel temperature. Continuity of temperature and thermal flux at the HE-wall boundary are assumed. The incremental heat loss is used to update the total heat loss and the average steel temperature.

(l) Current values of the state variables are printed optionally at multiples of the number of loops. Regardless of option, saved values--such as punch displacement and available heat--are stored.

(m) If the required terminal state has not been reached, loop back to (a) for another pass. Otherwise, stop and print final results. Among the final results are: volumetric increase in the HE due to elastic recovery and the associated decrease in HE density. (If a portion of the mass of RDX experienced grain fracture, some of the RDX strain energy would be thermalized, and the volumetric recovery would be smaller than calculated.)

14. Model Equations

The average density of the HE is, by definition, the ratio of HE mass, M, to volume, V. But, the volume of HE depends upon the cross section and length (or height) of the HE column. Denoting cross sectional area by A, initial column length by xo, and punch displacement by xp, the volume of the HE is given by

$$V = A(xo - xp), \qquad 0 \text{ le } xp \text{ le } xpmax. \quad (1)$$

Denoting the average (bulk HE) density by E(rho),

$$E(rho) = M/(A(xo - xp)) . \quad (2)$$

Altho not explicitly written as a function of displacement, the area A should be considered a function of xp, since the max hoop strain, eps, is a function of xp, and since

$$A = Ao(1 + eps)^2 , \quad (3)$$

where Ao is the unstrained, internal cross section of the body. A formula for E(rho) is derived in Ref 2d in terms of the theoretical maximum density of the HE, TMD, and of the punch pressure, p. This formula is repeated here:

$$E(rho)/TMD = 1 + (0.8/c)\ln((p+0.8-c)/(p+0.8)), \quad (4)$$

where c is the difference between maximum and minimum pressure within the volume of the HE. This result assumes a constant pressure gradient within the volume. The basis of the derivation is a constituative relationship between local HE density, rho, and local pressure, p:

$$rho/TMD = p/(p + 0.8), \quad (5)$$

where the constant 0.8 is given in kpsi.

Based on several experimental studies, cited in Ref 2d, the parameter c, which is a measure of the pressure gradient, is found to be directly proportional to the maximum pressure on the HE. Thus, parameter

$$c = g\,p\ , \tag{6}$$

where g is a constant. From Ref 2e, the value of g which best fits data on average bulk density is 0.6. This value is used here. (In earlier experiments at KSAAP and MAAAP, a value of 0.8 for g was indicated.)

15. Equation (4) for average density is not readily inverted in order to give punch pressure as a function of E(rho). This fact poses no problem numerically, however, since the relationship of these variables is monotonic. In a subroutine of COMPACT, punch pressure is calculated as a function of E(rho) by an iterative Newton-Raphson method. Given the punch pressure from (4), one can calculate the maximum hoop (i.e., tangential) stress within the wall of the cylindrical sleeve, representing the steel body, by Lame's formula (Ref 2h). The hoop stress at radius r is s(r):

$$s(r) = \frac{a^2\ b^2\,(p - po)}{(b^2 - a^2)\,r^2} + \frac{p\,a^2 - po\,b^2}{b^2 - a^2}\ , \tag{7}$$

where p is the pressure on the inside wall and po is the pressure on the outside of the wall. The internal radius of the sleeve is a and the outside radius b. The radius to an arbitrary point is r. In the present application, the maximum internal pressure is identified with the punch pressure, and the outside pressure is taken as atmospheric pressure, i.e., the outside of the wall is assumed unsupported. The maximum stress occurs at the inner wall, where r = a. The max body stress is, then,

$$s(a) = (p(a^2 + b^2) - 2\ po\ b^2)/(a^2 + b^2)\ . \tag{8}$$

If the body remains elastic thruout, the maximum strain is simply

$$eps = s(a)/Ey\ , \tag{9}$$

where Ey is Young's modulus for steel.
As indicated above, the cross section of the HE is related to xp functionally thru equations (2), (3), (4), (8), and (9).

16. The total hoop strain energy in the body is obtained by integrating the strain energy per unit volume,

$$s(r)^2/(2\ Ey)\ ,$$

over the volume of the cylinder wall subject to strain. Let the effective cylinder height experiencing this hoop strain be denoted by h. Then, using equation (7), the hoop strain energy is given by:

$$HSE = (\pi\ h/Ey)(T_1 + T_2 + T_3) , \tag{10}$$

where the indexed terms are functions of the dimensions a and b and of the punch pressure p.

$$T_1 = A^2 (b^2 - a^2)/(2 a^2 b^2) ,$$

$$T_2 = B^2 (b^2 - a^2)/2 ,$$

$$T_3 = 2 A B \ln(b/a) , \tag{11a}$$

where the auxiliary factors A and B are given by

$$A = (a^2 b^2 (p - po))/(b^2 - a^2)$$

$$B = (p a^2 - po\ b^2)/(b^2 - a^2) . \tag{11b}$$

Energy is also stored in the RDX crystals as elastic strain. If a local hydrostatic condition is assumed for each RDX particle, an expression for the total RDX strain energy can be derived by integrating stain energy per unit volume over the total volume. Let the bulk modulus of RDX be denoted by Bm. Also, let the pressure at a normalized axial coordinate x be denoted by p(x). The assumption of a constant pressure gradient in the HE means that

$$p(x) = p (1 - g x) , \qquad 0 \le x \le 1, \tag{12}$$

where, as above, p is the punch pressure and g is a constant. The RDX strain energy per unit volume, at x, is

$$p(x)^2/Bm/2.$$

By integrating this expression, with p(x) given in (12), over the total volume of RDX, Vr, one obtains the RDX strain energy, RSE:

$$RSE = (Vr\ p^2/(2\ Bm))(1 - g + g^2/3) . \tag{13}$$

Work performed by the punch is, of course, the source of both elastic and inelastic energy components. The punch work, W, is the integral over punch travel of

$$A\ p\ \delta(xp) , \tag{14}$$

where delta(xp) is the incremental displacement of the punch, given the constant punch pressure p and HE cross section A. For 3-digit accuracy the value of delta(xp) must be quite small--about 5 microns or less. At any instant, the total heat residing in the HE is the work performed by the punch minus (elastic) potential energy, of body and RDX, and minus heat energy lost to the body. The heat loss is relatively small, but is included to be complete. Denoting the available thermal energy in the HE by H and the heat lost by L, an energy balance requires that

$$H = W - HSE - RSE - L . \tag{15}$$

The average temperature rise, avgUh, of the HE, with heat capacity Ch is, then,

$$avgUh = H/Ch. \tag{16}$$

Similarly, the average temperature rise of the steel body, avgUs, is obtained from L and the heat capacity of the body, Cs:

$$avgUs = L/Cs . \tag{17}$$

17. A mathematically exact calculation of the heat loss from HE to body wall requires the solution of the diffusion equations in both HE and steel wall. The diffusion equation in the HE involves a heat source term, representing the rate of energy production per unit mass. To describe this source term requires an assumption concerning HE flow within the cavity, since viscous effects produce the heat. But, details of the HE flow are not modeled here. To escape this dilemma, I have simply assumed that the source term is independent of position (but, not of time). (Actually, this isotropic assumption implies something concerning HE flow, but is not pursued.) Denoting the rate of heat released per unit mass per unit time as Q, one can write

$$Q = delta(H)/delta(t)/M , \tag{18}$$

where delta(H) is the increment of heat added during the time increment delta(t). Notationally, let U(r) be the temperature at radial position r. When r is less than or equal to the inner radius, a, the temperature pertains to the HE. For r between a and outside radius, b, the temperature describes the steel wall. Further, let a terminal "1" indicate a property of the HE, and a terminal "2" indicate a property of the steel. Thus, alpha1 denotes the thermal diffusivity of HE, C1 denotes the specific heat of HE, and K1 denotes the thermal conductivity of HE. (The particular HE is Comp A-5.) Partial differentiation by r and by t are denoted, respectively, by subscripts r and t. With these conventions, the temperature in the HE is given by

$$U_t = (alpha1/r)(r\,U_r)_r + Q/C1 , \qquad 0 < r < a. \tag{19}$$

The diffusion equation for the cylindrical wall is:

$$U_t = (alpha2/r)(r\,U_r)_r , \qquad a < r < b. \tag{20}$$

Boundary conditions are needed at radial positions: 0, a, and b. At r = 0, cylindrical symmetry requires that no heat is transported across the center. Thus,

$$(U(0))_r = 0. \tag{21a}$$

At r = a, temperature is the same on each side of the boundry; and, the thermal flux out of the HE must equal flux into the steel wall.

$$U(a-) = U(a+)$$

and

$$K1\ (U(a-))_r = K2\ (U(a+))_r\ , \tag{21b}$$

where a- and a+ means r approaching a from below and from above, resp. Finally, the boundary at r = b can be treated as thermally insulated, since still air outside the cylinder is a good insulator.

$$(U(b))_r = 0. \tag{21c}$$

The rate of heat loss from HE is obtained from the following equation:

$$\text{delta}(L)/\text{delta}(t) = -K1\ \text{Awall}\ (U(a-))_r\ , \tag{22}$$

where Awall is the area of HE contacting the wall. The cumulative heat loss, L, is obtained by numerical integration of the time derivative in (22). A numerical solution of (19) thru (22) is obtained by a integrating a set of total differential equations for U(i), defined on a radial grid r(i), i=1,2,... . These equations are derived from (19,20,21) by a conventional forward-difference scheme. The implementing computer code is located on page A-7 of Annex A.

18. An Approximation for Heat Loss

Because the importance to this simulation of the heat loss from the HE is relatively small, the approach taken in paragraph 17 may entail too much computation. An approximation is given here which, tho not as accurate, may suffice. The approximate rate of loss makes use of the great difference in the thermal diffusivities of HE and steel. Because RDX has a very low diffusivity, heat loss is not felt very far into the HE from the cylinder wall. Therefore, a very steep temperature gradient exists in the HE near the wall. However, since heat diffuses rapidly in steel, a rather shallow radial temperature gradient gradient exists in the wall. Thus as a first approximation, the gradient in the steel is taken as zero, which implies that the temperature at the wall is nearly avgUs. Additionally, assume that the temperature in the HE drops linearly from avgUh to the value at the wall over a radial interval DELR. The negative gradient in the HE near the wall is approximated by

$$(\text{avgUh} - \text{avgUs})/\text{DELR}\ . \tag{23}$$

The approximate rate of heat loss from the HE is, from (22), the product of the factors Awall, K1, and the negative gradient in (23). The increment DELR is effectively the distance traveled internally from the wall at which the temperature rises linearly to avgUh. A natural length for measuring temperature change is the diffusion length, the distance a temperature spike will propagate by diffusion in time t. The diffusion length in the HE is

$$\mathrm{sqrt}(\mathrm{alpha1}\ t)\ . \tag{24}$$

Empirically, a good approximation for the temperature gradient at the wall, during the compression phase of loading, is obtained when DELR is 4 times the diffusion length.

19. Temperature in an RDX Particle

Among the physical processes occurring during loading, thermal diffusion in RDX particles appears to be of minor importance. If the heating rate of the surface of a typical RDX particle were sufficiently great, thermally (as well as mechanically) induced stresses might play a role in grain fracture. Actually, now this does not appear to be the case; but, this idea led to a study of the temperature profile with respect to radius in an RDX particle. The mean RDX particle diameter is about 160 microns for Class 1 RDX, which is presently being used in Comp A-5. Therefore, a spherical particle of this diameter was selected for the temperature study. The RDX specific surface--area per unit mass--was calculated for a uniform granulation of this diameter. Denoting the specific surface of the RDX by spS, the heat flux directed at a particle is given by

$$q = \mathrm{spS}\ Q\ (\mathrm{Mass\ RDX}/\mathrm{Mass\ HE})\ , \tag{25}$$

where the generation rate per unit mass of HE, Q, is given by (18). Notationally, let the RDX particle diameter be d, and let a terminal "3" denote a material property of RDX. Thus, K3 denotes the thermal conductivity of RDX. Additionally, denote the RDX temperature rise at particle radius r by U(r). With this notation and subscript conventions, one can write the boundary condition at the surface of the typical particle as

$$q = -K3\ (U(d/2))_r\ , \tag{26}$$

assuming that all the flux is absorbed.
By spherical symmetry, the boundary condition at particle center is:

$$(U(0))_r = 0. \tag{27}$$

These boundary conditions are applied to the spherically symmetric form of the diffusion equation in a particle. Functional dependence of U upon r is suppressed here:

$$U_t = \mathrm{alpha3}\ (\ (2/r)U_r + U_{rr}\ )\ , \qquad 0 < r < d/2. \tag{28}$$

Solution of the RDX diffusion equations is an option in the program COMPACT. The numerical method uses a radial grid of points at which the temperature is evaluated. The differential equations on this grid are developed from (28) using a central-difference approximation to spatial derivatives. An update is performed using two half-steps at each step in time. Equations are found on page A-8 in Annex A. Quite small time steps, delta(t), are required for numerical stability of this method. To insure that stability is met, the incremental punch travel, delxp, is kept small (1 micron), since this and punch speed, implicitly determine delta(t). Additionally, when calculating RDX particle temperature, the initial punch speed is taken to be its maximum value, (with a slight loss of fidelity to kinematics).

DISTRIBUTION

Copies		
1	HQDA WASH DC 20310	DAMO-ZA
1	HQDA WASH DC 20310	DALO-SMZ
	COMMANDER USAMC 5001 EISENHOWER AVE. ALEXANDRIA, VA 22333-0001	
1	ATTN:	AMCRE-IP
1		AMCPA-S
1		AMCDP
	DIRECTOR, US AMSAA ABERDEEN PG, MD 21005-5066	
1	ATTN:	AMXSY-DL
1		AMXSY-MP, Herb Cohen
	COMMANDER USA COMMUNICATIONS AND ELECTRONICS COMMAND FT MONMOUTH, NJ 07703-5304	
1	ATTN:	AMSEL-PL-SA
	COMMANDER CECOM (R&D) FT MONMOUTH, NJ 07703-5304	
1	ATTN:	AMSEL-SAD
	COMMANDER USAMICOM REDSTONE ARSENAL, AL 35809-5060	
1	ATTN:	AMSMI-DS
	COMMANDER USATACOM WARREN, MI 48090	
1	ATTN:	AMSTA-V
	OFFICE OF PROJECT MGR CANNON ARTY WPNS DOVER, NJ 07801-5001	
1	ATTN:	AMCPM-CAWS
	COMMANDER, US ARMY LOGISTICS CENTER FORT LEE, VA 23801	
1	ATTN:	ATCL-S

1 COMMANDER
DEFENSE LOGISTIC STUDIES
INFORMATION EXCHANGE
FORT LEE, VA 23801

COMMANDER
USA LOGISTICS EVAL AGENCY
NEW CUMBERLAND ARMY DEPOT
NEW CUMBERLAND, PA 17070
1 ATTN: DAL-LEM

COMMANDER USATECOM
ABERDEEN PG, MD 21005-5055
1 ATTN: AMSTE-SY

12 DEFENCE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VA 22314

COMMANDER US AMCCOM (D)
DOVER, NJ 07801-5001
1 ATTN: SMCAR- -FSP-A (D), Dick Collett
3 -FSM (D), Dom Demella,
Keith Fulton, &
Werner Fields
2 -AEE (D), Steve Belden,
Michael Joyce, &
Wally Voreck
1 -AST (D), Gus Magistro
1 -ASH (D), Larry Ostuni
1 -QAQ (D), Thomas Wu

COMMANDER US AMCCOM (R)
ROCK IS, IL 61299-6000
1 ATTN: AMSMC- -ASM (R), Roger Newlon
1 -IRC (R), George Cowan
1 -OPP (R), Jim De Wulf
1 -PDM (R), Bob Marcuson
2 -QAL (R), Arlen Dillin &
Curt Carlson
2 -SF (R), Glenn Leach &
Anna Francis
6 -RDA (R), Bernard Witherspoon
1 ATTN: SMCAR-ESP-L
2 ATTN: SMCAR-ESM-M (R), Bill Fortune &
Joe Menke
1 ATTN: SMCAR-ESM-L (R), Larry Randol

COMMANDER
ROCK ISLAND ARSENAL
ROCK IS, IL 61299-6000
1 ATTN: SMCRI-EN, Duane Moberg

COMMANDER
CHEMICAL R AND D CENTER
ABERDEEN PROVING GROUND
(EDGEWOOD AREA), MD 21010-5423
1 ATTN: AMSMC-CLJ-IA (A)

DIRECTOR US AMETA
ROCK IS, IL 61299-6000
1 ATTN: AMXOM-QA

DIRECTOR
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CA 93940
1 ATTN: DEPT OF OPERATIONS ANAL.

DIRECTOR
USA TRASANA
WHITE SANDS MISSILE RANGE
WHITE SANDS, NM 88002-5502
1 ATTN: ATAA-SL

COMMANDER
KANSAS AAP
PARSONS, KA 67357
2 ATTN: Ops Review, Luther Bailey & Jerry Boyd (Day & Zimmerman)

COMMANDER
LONE STAR AAP
TEXARKANA, TX 75551
2 ATTN: SMCLS-EN, Gary Hodgson & Jerry Molito

COMMANDER
MILAN AAP
MILAN, TN 38358-5000
1 ATTN: SMCMI-EN, Patrick Brew

DAY & ZIMMERMAN, INC
LSAAP TECHNICAL DEPT
TEXARKANA, TX 75501
2 ATTN: Bud Formby & Dillard Baker

ANNEX A

SOURCE PROGRAM FOR SIMULATING THE STATE OF AN
M42/M46 GRENADE DURING PRESS LOADING

```
PREAMBLE ''COMPACT
NORMALLY MODE IS REAL
DEFINE PRESS AS A REAL FUNCTION GIVEN 2 ARGUMENTS
DEFINE RHOTRANS AS A REAL FUNCTION GIVEN 2 ARGUMENTS
DEFINE STRN.ENER AS A REAL FUNCTION GIVEN 2 ARGUMENTS
DEFINE ESTRN.RDX AS A REAL FUNCTION GIVEN 1 ARGUMENT
DEFINE RPSPEED AS A REAL FUNCTION GIVEN 1 ARGUMENT
DEFINE FLAGU AS AN INTEGER VARIABLE
DEFINE EYOUNG,LBODY,RINT,ROUT,GRAD.PRS,XPMAX AS REAL VARIABLES
DEFINE BM.RDX,EY.RDX,PR.RDX,VOL.RDX AS REAL VARIABLES
END ''PREAMBLE

MAIN ''COMPACT
''
''PROGRAM SIMULATES THE COMPACTION OF THE HE AND THE STRAINING OF THE
''GRENADE BODY DURING PRESS LOADING OF AN M42 GRENADE.  A BODY IS REP-
''RESENTED AS A CYLINDRICAL SLEEVE OF CONSTANT HEIGHT.
''
''PARAMETERS:
''MASSHE ____ MASS OF THE HE (G).
''AXHE ______ CROSS-SECTIONAL AREA (SQ CM) OF THE HE DURING PRESSING.
''AXHEO _____ INITIAL CROSS-SECTION OF THE HE (SQ CM)
''RINT ______ INITIAL INTERNAL RADIUS OF THE GRENADE (CM).
''ROUT ______ INITIAL OUTSIDE RADIUS OF THE GRENADE (CM).
''LBODY _____ EFFECTIVE LENGTH OF THE BODY SUBJECT TO HOOP STRAIN (CM).
''XO _______ INITIAL EFFECTIVE HEIGHT OF THE HE CYLINDER (CM).
''XP _______ DISPLACEMENT OF THE PUNCH (CM).
''XPMAX _____ MAX DISPLACEMENT OF THE PUNCH (CM).
''DELXP _____ INCREMENT IN DISPLACEMENT OF THE PUNCH (CM).
''RHOHEO ____ DENSITY OF THE HE PRIOR TO FINAL CONSOLIDATION (G/CC).
''RHOHE _____ AVG DENSITY OF THE HE DURING CONSOLIDATION (G/CC).
''TMDHE _____ THEORETICAL MAX DENSITY OF THE HE (G/CC).
''PHE _______ PRESSURE ON THE HE (KPSI) DURING CONSOLIDATION.
''PINT ______ INTERNAL PRESSURE ON THE HE BODY (PASCAL).
''POUT ______ OUTSIDE PRESSURE ON THE BODY (PA).
''MAXKPSI ___ MAX PRESSURE (KPSI) TO STOP THE SIMULATION.
''EYOUNG ____ YOUNG'S MODULUS OF THE BODY STEEL (PA).
''DENS.STEEL  DENSITY OF STEEL IN BODY (G/CC).
''SPHT.STEEL  SPECIFIC HEAT OF STEEL (CAL/G/DEG K).
''TCOND.STEEL THERMAL CONDUCTIVITY OF STEEL (CAL/CM/S/DEG K).
''DIFUZ.STEEL THERMAL DIFFUSIVITY  OF STEEL (SQ CM/S).
''SIGPA _____ BODY HOOP STRESS (PA).
''SIGKPSI ___ BODY HOOP STRESS (KPSI).
''HSTRAIN ___ BODY HOOP STRAIN.
''GRAD.PRS __ COEFFICIENT FOR THE PRESSURE GRADIENT WITHIN THE HE.
''MASS.RDX __ MASS OF RDX IN HE (G).
''FRACT.RDX _ MASS FRACTION OF RDX IN HE.
''VOL.RDX __ VOLUME OF RDX CRYSTALLS (CC).
''BM.RDX ____ BULK MODULUS OF RDX (PA).
''EY.RDX ____ YOUNG'S MODULUS FOR RDX (PA).
''PR.RDX ____ POISSON'S RATIO FOR RDX.
''SPS.RDX ___ SPECIFIC SURFACE FOR RDX (SQ CM/G).
```

```
''TMD.RDX ___ THEOPETICAL MAX DENSITY OF RDX (G/CC).
''SPHT.RDX __ SPECIFIC HEAT OF RDX (CAL/G/DEG K).
''TCOND.RDX _ THERMAL CONDUCTIVITY OF RDX (CAL/CM/S/DEG K).
''DIFUZ.RDX _ THERMAL DIFFUSIVITY OF RDX (SQ CM/S)
''MASS.STER _ MASS STERIC ACID (G).
''DENS.STER _ DENSITY OF STERIC ACID (G).
''SPHT.STER _ SPECIFIC HEAT OF STERIC ACID (CAL/G/DEG K).
''HSE _______ BODY (ELASTIC) HOOP-STRAIN ENERGY (JOULE).
''EE.RDX ____ ELASTIC ENERGY IN THE RDX CRYSTALS (JOULE)
''HENERGY ___ (THERMAL) ENERGY AVAILABLE FOR HEATING THE RDX.
''DELTAR ____ SPACE INTERVAL IN RDX-PARTICLE RADIAL GRID (CM).
''DELTAT ____ TIME STEP IN INTEGRATING THE HEAT THANSFER DIFF EQNS.
''
DEFINE FLAGUHE,I,J,K,KPRINT,KUPRINT,L,M,N,NGRID,NHE,NST AS INTEGER
VARIABLES
DEFINE ANSWER AS A TEXT VARIABLE
DEFINE UV,UOV,U1V AS REAL, 1-DIMENSIONAL ARRAYS ''RDX PARTICLE TEMP
DEFINE UHEV,UHEOV,USTV,USTOV AS REAL, 1-DIMENSIONAL ARRAYS ''HE TEMP
''
''ASSIGN CONSTANTS.
''
    LET FLAGUHE=0 ''IS 1 TO FLAG CALC OF RADIAL DIST OF UHE
    LET NGRID=11
    LET NHE=21
    LET NST=5
    LET DELTAR=0.0008 ''CM STEP IN RDX XTAL (8 MICRON)
    RESERVE UV(*),UOV(*),U1V(*) AS NGRID
    RESERVE UHEV(*),UHEOV(*) AS NHE
    RESERVE USTV(*),USTOV(*) AS NST
    FOR I=1 TO NHE, LET UHEOV(I)=0.0
    FOR I=1 TO NST, LET USTOV(I)=0.0
    FOR I=1 TO NGRID DO
        LET UV(I)=0.0
        LET UOV(I)=0.0
        LET U1V(I)=0.0
    LOOP ''TO INITIALIZE THE RDX TEMPERATURE PROFILE
    LET HTLOSS=0.0
    LET KPRINT=10
    LET KUPRINT=100
    LET DELXP=0.0001
    LET GRAD.PRS=0.6
    LET PA.KPSI=6.89474*10**6 ''PASCALS PER KPSI CONVERSION
    LET CALPJ=0.239 ''CALORIES PER JOULE CONVERSION
    LET EYOUNG =2.06843*10**11 ''PA.  YOUNG'S MODULUS FOR STEEL
    LET DENS.STEEL=7.87 ''G/CC
    LET SPHT.STEEL=0.125 ''CAL/G/DEG K
    LET TCOND.STEEL=0.165 ''CAL/CM/S/DEG K
    LET DIFUZ.STEEL=TCOND.STEEL/DENS.STEEL/SPHT.STEEL
    LET LBODY=3.556
    LET RINT=1.6256 ''FOR 110 MIL WALL THICKNESS
''  LET RINT=1.6002 FOR 120 MIL WALL THICKNESS
''  LET RINT=1.6130
    PRINT 2 LINES WITH RINT
    THUS
CURRENT VALUE OF INTERNAL RADIUS IS *.**** CM, FOR A 110 MIL WALL THICKNESS.
INPUT THE VALUE OF RINT WANTED.  NOTE:  1.6002 (120 MIL WALL THICKNESS).
    READ RINT
    LET ROUT=1.9050 ''CM
```

```
        LET DRHE=RINT/(NHE-1)
        LET DRST=(ROUT-RINT)/(NST-1)
        LET POUT=1.01353*10**5 ''PA (14.7 PSI)
        PRINT 1 LINE THUS
 INPUT THE MAX PUNCH PRESSURE, IN KPSI, TO STOP SIMULATION.
        READ MAXKPSI
        LET AXHEO=PI.C*RINT**2
        LET AXHE=AXHEO ''INITIALLY
        LET MASSHE=30.0 ''G
        LET FRACT.RDX=0.985 ''FRACTION OF RDX IN HE
        LET MASS.RDX=MASSHE*FRACT.RDX
        LET MASS.STER=MASSHE-MASS.RDX
        LET SPHT.STER=0.399
        LET DENS.STER=0.847
        LET TCOND.STER=3.8/10**4
        LET HTCAP.STER=MASS.STER*SPHT.STER ''CAL/DEG K
        LET TMD.RDX=1.82 ''G/CC
        LET TMDHE=1.78 ''G/CC FOR COMP A-5
        LET VOL.RDX=MASS.RDX/TMD.RDX ''VOLUME (CC) OF RDX CRYSTALS
        LET RAD.RDX=(NGRID-1)*DELTAR
        LET NPARTICLES=VOL.RDX/PI.C/4.0*3.0/RAD.RDX**3
        LET SPS.RDX=NPARTICLES*4.0*PI.C*RAD.RDX**2/MASS.RDX
        LET SPHT.RDX=0.300 ''CAL/G/DEG K
        LET HTCAP.RDX=MASS.RDX*SPHT.RDX
        LET TCOND.RDX=0.0007 ''CAL/CM/S/DEG K
        LET DIFUZ.RDX=TCOND.RDX/TMD.RDX/SPHT.RDX
        LET FRACT.STER=1.0-FRACT.RDX
        LET SPHT.HE=FRACT.RDX*SPHT.RDX+FRACT.STER*SPHT.STER
        LET TCOND.HE=FRACT.RDX*TCOND.RDX+FRACT.STER*TCOND.STER
        LET DENS.HE=1.0/(FRACT.RDX/TMD.RDX+FRACT.STER/DENS.STER)
        LET DIFUZ.HE=TCOND.HE/DENS.HE/SPHT.HE
        LET UCON.HE=DIFUZ.HE/DRHE/DRHE
        LET UCON.ST=DIFUZ.STEEL/DRST/DRST
        LET DTIME=0.27 ''(S) TIME FOR TEMP DIFFUSION
        LET DL.HE=SQRT.F(DIFUZ.HE*DTIME) ''(CM) DIFFUSION LENGTH IN HE
        LET DELR.HE=4.0*DL.HE ''(CM) FOR APPROX THERM GRAD IN HE AT WALL
        LET B[illegible]=TCOND.HE*DRST/TCOND.STEEL/DRHE
        LET [illegible]=1.0/(1.0+BETA)
        LET [illegible]=DIFUZ.RDX/DELTAR**2
        LET UOCON=DELTAR/TCOND.RDX
        LET U1CON=DIFUZ.RDX/DELTAR
        LET EY.RDX=1.8*10**10 ''YOUNG'S CONSTANT FOR RDX (PA)
        LET PR.RDX=0.22  ''POISSON'S RATIO FOR RDX
        LET BM.RDX=EY.RDX/3.0/(1.0-2.0*PR.RDX) ''BULK MODULUS FOR RDX
  ''
  ''GET INITIAL HE DENSITY FROM THE TERMINAL.
  ''
        PRINT 1 LINE THUS
 INPUT THE INITIAL DENSITY OF THE HE.  SUGGEST 1.440 G/CC.
        READ RHOHEO
        PRINT 1 LINE THUS
 DO YOU WANT THE TEMPERATURE PROFILE IN AN RDX PARTICLE?  (Y OR N).
        READ ANSWER
        IF SUBSTR.F(ANSWER,1,1) = "Y"
            LET FLAGU=1
        OTHERWISE
            LET FLAGU=0
```

```
    ALWAYS
''
''GET INITIAL HEIGHT OF HE CYLINDER.
''
    LET VOL.HEO=MASSHE/RHOHEO
    LET XO=VOL.HEO/AXHEO
''
''CALCULATE INITIAL BODY STRAIN DUE TO PRECONSOLIDATION.
''
    LET PHE=PRESS(TMDHE,RHOHEO)
    LET PINT=PA.KPSI*PHE
    LET PINTO=PINT
    LET EE.RDX=ESTRN.RDX(PINTO) ''RDX STRAIN ENERGY FOR PRECONSOL COND
    CALL STRS.STRAIN (PINT,POUT) YIELDING SIGPA, HSTRAIN
    LET SIGKPSI=SIGPA/PA.KPSI
    LET HSTRESS=SIGPA/10**6
''
''GET CROSS-SECTION OF HE, ACCOUNTING FOR BODY STRAIN.
''
    LET AXHE=AXHEO*(1.0+ABS.F(HSTRAIN))**2
''
''REEVALUATE HEIGHT OF HE COLUMN TO GIVE DESIRED DENSITY.
''
    LET XO=MASSHE/RHOHEO/AXHE
''
''GET MAX HOOP STRAIN AND MAX DENSITY.
''
    CALL STRS.STRAIN (MAXKPSI*PA.KPSI,POUT) YIELDING MAXSIGPA,MAXSTRAIN
    LET MAXRHO=RHOTRANS(TMDHE,MAXKPSI) + 0.0001
    LET XPMAX=XO-MASSHE/MAXRHO/AXHEO/(1.0+ABS.F(MAXSTRAIN))**2 + 0.007
    LET AWALL=2.0*PI.C*(RINT*XO+RINT**2) ''WALL AREA FOR HEAT LOSS
    LET HVOL.STEEL=AWALL*(ROUT-RINT) ''VOL OF STEEL HEATED BY HE LOSS
    LET HTCAP.STEEL=HVOL.STEEL*DENS.STEEL*SPHT.STEEL
    LET USTEEL=0.0 ''INITIALIZATION OF TEMPERATURE OF STEEL BODY
    LET HSE=STRN.ENER (PINT,POUT)
    LET PWORK=HSE+EE.RDX
    LET HENERGY0=0.0 ''INITIAL HEAT ENERGY DEFINED AS ZERO (REFERENCE)
    LET TIME=0.0
    LET XP=0.0
    LET XPO=XP
    LET HOLDXP=0.0
    SKIP 2 LINES
    PRINT 5 LINES WITH 2*RINT,2*RINT/2.54,2*ROUT,2*ROUT/2.54,LBODY,
    LBODY/2.54,XPMAX,XPMAX/2.54
    THUS
DIMENSIONS OF CYLINDRICAL SLEEVE SIMULATING THE GRENADE BODY
INTERNAL DIAMETER  ___  *.****  CM  ___  *.****  INCH
OUTSIDE  DIAMETER  ___  *.****  CM  ___  *.****  INCH
EFFECTIVE HEIGHT   ___  *.****  CM  ___  *.****  INCH
PUNCH TRAVEL LIMIT ___  *.****  CM  ___  *.****  INCH
    SKIP 2 LINES
    PRINT 15 LINES WITH 20000*RAD.RDX,10000*DELTAR,SPS.RDX,TMD.RDX,
    SPHT.RDX,TCOND.RDX,DIFUZ.RDX,EY.RDX,PR.RDX,BM.RDX,FRACT.RDX
    THUS
PROPERTIES OF RDX , USED IN THE EXPLOSIVE FILL:
```

```
DIAMETER OF RDX PARTICLE  ______      ***.*  MICRON
RADIAL GRID ELEMENT OF RDX ______     ***.*  MICRON
SPECIFIC SURFACE OF RDX ______        ***.*  SQ CM/G
THEORETICAL MAX DENSITY OF RDX _      *.***  G/CC
SPECIFIC HEAT OF RDX __________       *.***  CAL/G/DEG K
THERMAL CONDUCTIVITY OF RDX ___       ............. CAL/CM/S/DEG K
THERMAL DIFFUSIVITY  OF RDX ___       ............. SQ CM/S
YOUNG'S CONSTANT FOR RDX ______       ............. PASCAL
POISSON'S RATIO  FOR RDX ______       .............
BULK MODULUS FOR RDX __________       ............. PASCAL
MASS FRACTION OF RDX IN HE ____       *.***
_________________________________________________________________________

          PRINT 15 LINES WITH DRHE,DENS.HE,SPHT.HE,TCOND.HE,DIFUZ.HE,DRST,
          DENS.STEEL,SPHT.STEEL,TCOND.STEEL,DIFUZ.STEEL
          THUS
THERMAL PROPERTIES OF GRENADE MATERIALS:
_________________________________________________________________________
RADIAL GRID ELEMENT OF HE ____        ............. CM
TMD OF HE ______________________      ............. G/CC
SPECIFIC HEAT OF HE ____________      ............. CAL/G/DEG K
THERMAL CONDUCTIVITY OF HE ___        ............. CAL/CM/S/DEG K
THERMAL DIFFUSIVITY  OF HE ___        ............. SQ CM/S
RADIAL GRID ELEMENT OF STEEL __       ............. CM
TMD OF STEEL ___________________      ............. G/CC
SPECIFIC HEAT OF STEEL _________      ............. CAL/G/DEG K
THERMAL CONDUCTIVITY OF STEEL _       ............. CAL/CM/S/DEG K
THERMAL DIFFUSIVITY  OF STEEL _       ............. SQ CM/S
_________________________________________________________________________

          PRINT 9 LINES WITH RHOHEO,PHE,PINT/1000000,XO,SIGKPSI,HSTRESS,
          HSTRAIN,HSE,HSE*CALPJ,EE.RDX,EE.RDX*CALPJ,PWORK,PWORK*CALPJ
          THUS
INITIAL CONDITIONS AT START OF FINAL CONSOLIDATION:
HE DENSITY ___________  *.*****  G/CC
PRESSURE ON HE _______  **.****  KPSI ___  ***.***  MPA
HEIGHT OF HE COLUMN __  *.*****  CM
MAX BODY HOOP STRESS _  ***.***  KPSI ___  ****.**  MPA
HOOP STRAIN IN BODY __  ............
HOOP STRAIN ENERGY ___  **.****  JOULE ___  **.****  CAL
RDX ELASTIC ENERGY ___  **.****  JOULE ___  **.****  CAL
CUM WORK BY PUNCH ____  **.****  JOULE ___  **.****  CAL
          SKIP 2 LINES
          PRINT 7 LINES THUS
SIMULATED CONDITIONS DURING HE CONSOLIDATION

_____________________________________________________________________________________
PUNCH   HE      HE      MAX      HOOP    H STRN   PUNCH   THERM   TEMP    CYCLE
DISPL   DENS    PRESS   STRESS   STRAIN  ENERGY   WORK    WORK    RISE    TIME
(CM)    (G/CC)  (KPSI)  (KPSI)   (MU/U)  (CAL)    (CAL)   (CAL)   (D K)   (MS)
_____________________________________________________________________________________
          WHILE XP < XPMAX, DO
    ''
    ''INCREMENT DISPLACEMENT OF THE PUNCH.
    ''
              ADD DELXP TO XP
```

```
        LET HOLDXP=XP
''
''CALC VOLUME AND DENSITY OF HE W/O ACCOUNTING FOR ADD'NL BODY STRAIN.
''
        LET RHOHE=MASSHE/AXHE/(X0-XP)
        LET PHE=PRESS(TMDHE,RHOHE)
        LET PINT=PA.KPSI*PHE
''
''CALCULATE INCREMENT OF WORK DONE BY PUNCH AT THIS PRESSURE.
''
        LET DELPWORK=0.000001*AXHE*PINT*DELXP
        ADD DELPWORK TO PWORK
''
''CALCULATE BODY STRAIN AT THIS PRESSURE.
''
        CALL STRS.STRAIN (PINT,POUT) YIELDING SIGPA,HSTRAIN
        LET SIGKPSI=SIGPA/PA.KPSI
''
''OBTAIN NEW CROSS SECTION, ACCOUNTING FOR CURRENT STRAIN.
''
        LET AXHE=AXHE0*(1.0+HSTRAIN)**2
''
''FIND THE ADDITIONAL PUNCH DISPLACEMENT WHICH PRESERVES HE DENSITY.
''
        LET XP=X0-MASSHE/AXHE/RHOHE
''
''ADD THE ADDITIONAL PUNCH WORK FOR THE ADDITIONAL DISPLACEMENT.
''
        DELPWORK=0.000001*AXHE*PINT*(XP-HOLDXP)
        ADD DELPWORK TO PWORK
''
''UPDATE TIME.
''
        LET DELTAT=(XP-XP0)*RPSPEED(XP)
        LET DELT2=0.5*DELTAT
        ADD DELTAT TO TIME
''
''CALCULATE THE HOOP STRAIN ENERGY.
''
        LET HSE=STRN.ENER (PINT,POUT)
''
''CALCULATE THE ELASTIC STRAIN ENERGY IN THE RDX.
''
        LET EE.RDX=ESTRN.RDX(PINT)
''
''CALCULATE THE THERMAL ENERGY BALANCE.
''
        LET HENERGY=MAX.F(0.0,PWORK-HSE-EE.RDX-HTLOSS)
''
''CALCULATE THE THERMAL FLUX TO THE RDX.
''
        LET QDOT=CALPJ*(HENERGY-HENERGY0)/(MASS.RDX*SPS.RDX)/DELTAT
''
''CALCULATE AVG TEMP RISE IN HEATED HE.
''
        LET UHE=HENERGY*CALPJ/(HTCAP.RDX+HTCAP.STER)
''
```

```
''CALCULATE HEAT LOSS TO WALL.
''
          IF FLAGUHE NE 1
               GO TO L3
          OTHERWISE ''GET RADIAL DIST OF TEMP IN HE AND IN STEEL WALL
          IF UCON.HE*DELTAT > 0.25
               GO TO L3 ''TO AVOID NUMERICAL INSTABILTY
          OTHERWISE
          IF UCON.ST*DELTAT > 0.25
               GO TO L3 ''TO AVOID NUMERICAL INSTABILITY
          OTHERWISE
          LET TIMEU=TIME
          LET OMEGA=QDOT*MASS.RDX*SPS.RDX/MASSHE ''HEAT GEN RATE/MASSHE
          FOR I=2 TO NHE-1 DO
               LET RIA=DRHE*I
               LET RI=RIA-DRHE
               LET UHEV(I)=UHEOV(I)+DELTAT*UCON.HE/RI*(RIA*(UHEOV(I+1)
               -UHEOV(I))-RI*(UHEOV(I)-UHEOV(I-1)))+DELTAT*OMEGA/SPHT.HE
               LET UHEV(I)=MAX.F(0.0,UHEV(I))
          LOOP ''OVER HE GRID
          LET UHEV(1)=UHEV(2) ''AT CENTER OF HE
          FOR I=2 TO NST-1 DO
               LET RIA=RINT+DRST*I
               LET RI=RIA-DRST
               LET USTV(I)=USTOV(I)+DELTAT*UCON.ST/RI*(RIA*(USTOV(I+1)
               -USTOV(I))-RI*(USTOV(I)-USTOV(I-1)))
               LET USTV(I)=MAX.F(0.0,USTV(I))
          LOOP ''OVER STEEL GRID
          LET USTV(NST)=USTV(NST-1) ''FOR INSULATED OUTER BOUNDARY
''
''AT HE-STEEL BOUNDARY, CONSERVE FLUX AND TEMPERATURE.
''
          LET UHEV(NHE)=(BETA*UHEV(NHE-1)+USTV(2))*ROPB
          LET USTV(1)=UHEV(NHE)
          LET DELHTLOSS=AWALL*TCOND.HE*(UHEV(NHE-1)-UHEV(NHE))/DRHE*
          DELTAT/CALPJ
''
''UPDATE INITIAL CONDITIONS.
''
          FOR I=1 TO NHE, LET UHEOV(I)=UHEV(I)
          FOR I=1 TO NST, LET USTOV(I)=USTV(I)
          GO TO L4
'L3'      LET DELHTLOSS=AWALL*TCOND.HE*(UHE-USTEEL)/DELR.HE*DELTAT/CALPJ
'L4'      ADD DELHTLOSS TO HTLOSS
          LET USTEEL=HTLOSS/HTCAP.STEEL*CALPJ
          ADD 1 TO K
          IF FLAGUHE NE 1
               GO TO L6
          OTHERWISE
          IF MOD.F(K,KUPRINT) NE 0
               GO TO L6
          OTHERWISE
          SKIP 1 LINE
          PRINT 5 LINES WITH 1000*TIMEU
          THUS
TEMP DIST IN GRENADE AT TIME ***.*** MS
```

```
HE  RADIAL        TEMP INCR      LOCATION
LOC (CM)          (DEG K)        INDEX
_______________________________________
            FOR I=1 TO NHE DO
                LET J=I-1
                LET R=DRHE*J
                PRINT 1 LINE WITH R,UHEV(I),I
                THUS
 **.****          ***.****       **
            LOOP ''OVER HE GRID
            PRINT 4 LINES THUS
_______________________________________
WALL RADIAL       TEMP INCR      LOCATION
LOC (CM)          (DEG K)        INDEX
_______________________________________
            FOR I=1 TO NST DO
                LET J=I-1
                LET R=DRST*J+RINT
                PRINT 1 LINE WITH R,USTV(I),J+NHE
                THUS
 **.****          ***.****       **
            LOOP ''OVER ST GRID
            PRINT 2 LINES THUS
_______________________________________

     'L6'   IF FLAGU=0
                GO TO L5
            OTHERWISE ''GET TEMP PROFILE IN RDX PARTICLE
            IF UCON*DELT2 > 0.25
                GO TO L5 ''TO AVOID NUMERICAL INSTABILITY
            OTHERWISE
            LET U1V(2)=UOV(2)+DELT2*UCON*(UOV(3)-UOV(2))
            LET U1V(1)=U1V(2)  ''FOR ZERO COND AT CENTER OF PARTICLE
            FOR I=3 TO NGRID-1 DO
                LET RI=(I-1)*DELTAR
                LET U1V(I)=UOV(I)+DELT2*U1CON*((UOV(I+1)-UOV(I-1))/RI +
                (UOV(I+1)-2.0*UOV(I)+UOV(I-1))/DELTAR)
            LOOP ''OVER GRID
            LET U1V(NGRID)=U1V(NGRID-1)+UOCON*QDOT
     ''
     ''MOVE NEXT HALF-TIME STEP.
     ''
            LET UV(2)=U1V(2)+DELT2*UCON*(U1V(3)-U1V(2))
            LET UV(1)=UV(2) ''AT CENTER
            FOR I=3 TO NGRID-1 DO
                LET RI=(I-1)*DELTAR
                LET UV(I)=U1V(I)+DELT2*U1CON*((U1V(I+1)-U1V(I-1))/RI +
                (U1V(I+1)-2.0*U1V(I)+U1V(I-1))/DELTAR)
            LOOP ''OVER GRID
            LET UV(NGRID)=UV(NGRID-1)+UOCON*QDOT
     ''
     ''UPDATE INITIAL TEMPERATURE DISTRIBUTION.
     ''
            FOR I=1 TO NGRID, LET UOV(I)=UV(I)
     ''
     ''PRINT TEMPERATURES AS REQUIRED.
     ''
```

```
IF MOD.F(K,KUPRINT) NE 0
    GO TO L5
OTHERWISE
SKIP 1 LINE
PRINT 5 LINES WITH 1000*TIME
THUS
TEMP DISTRIBUTION IN RDX AT TIME ***.*** MS
________________________________________________________
RDX  RADIAL      TEMP INCR      LOCATION
LOC (MICRON)     (DEG K)        INDEX
________________________________________________________
FOR I=1 TO NGRID DO
    LET J=I-1
    LET R=10000.0*DELTAR*J
    PRINT 1 LINE WITH R,UV(I),J
    THUS
 ****.****       ***.***         **
LOOP ''OVER GRID
PRINT 2 LINES THUS

________________________________________________________
'L5'    IF PHE GE MAXKPSI
            GO TO L2
        OTHERWISE
        IF MOD.F(K,KPRINT) NE 0
            GO TO L1
        OTHERWISE
        PRINT 1 LINE WITH XP,RHOHE,PHE,SIGKPSI,10**6*HSTRAIN,CALPJ*
        HSE,CALPJ*PWORK,CALPJ*HENERGY,UHE,1000*TIME
        THUS
*.****  *.****  **.***  ***.**  ****.*  **.***   **.***  **.***  **.***  ***.**
'L1'    LET XPO=XP
        LET HENERGYO=HENERGY
    LOOP ''OVER DISPLACEMENT
'L2'    PRINT 1 LINE WITH XP,RHOHE,PHE,SIGKPSI,10**6*HSTRAIN,CALPJ*
        HSE,CALPJ*PWORK,CALPJ*HENERGY,UHE,1000*TIME
        THUS
*.****  *.****  **.***  ***.**  ****.*  **.***   **.***  **.***  **.***  ***.**
    PRINT 2 LINES THUS

__________________________________________________________________________________
''
''FOR THE RDX IN THE HE, GET THE STRAIN, STRAIN ENERGY, VOL RECOVERY,
''AND THE FINAL DENSITY OF THE HE.
''
    LET EPS.RDX=PINT/EY.RDX
    LET EE.RDX=ESTRN.RDX(PINT) ''JOULE
    LET DVOL.RDX=VOL.RDX*PINT/BM.RDX
    LET DVOL.HE=VOL.RDX*EPS.RDX*(1.0+2.0*PR.RDX) ''UNI-AXIAL RELEASE
    LET VOL.HE=MASSHE/RHOHE
    LET RHOHE=RHOHE*VOL.HE/(VOL.HE+DVOL.HE) ''DENS AFTER RECOVERY
''
''HOOP STRESS ON THE OUTSIDE OF THE BODY AT AN INT PRESS OF PINT.
''
    LET A=0.01*RINT
    LET B=0.01*ROUT
    LET DENOM=B**2-A**2
```

```
      LET SIGOUT=(A**2*(PINT-POUT)+PINT*A**2-POUT*B**2)/DENOM
      LET MAXLOAD=PI.C*(RINT/2.54)**2*PHE
      PRINT 3 LINES WITH PINT/PA.KPSI,MAXLOAD,SIGOUT/PA.KPSI
      THUS
MAX CONSOLIDATION PRESSURE  ____  ***.***  KPSI
MAX CONSOLIDATION LOAD ________   ***.***  KLBF
HOOP STRESS ON BODY OUTSIDE ___   ***.***  KPSI
      PRINT 10 LINES WITH 10**6*EPS.RDX,VOL.RDX,DVOL.RDX,100*DVOL.RDX/
      VOL.RDX,DVOL.HE,100*DVOL.HE/VOL.HE,RHOHE,EE.RDX,CALPJ*EE.RDX,
      HTLOSS,CALPJ*HTLOSS,USTEEL,1000*TIME,QDOT
      THUS
STRAIN IN BULK RDX ___   ******.*  MU/U
VOLUME OF RDX SOLID __   ***.****  CC
RDX VOLUME INCREASE __   ***.****  CC  (**.***%)
1-AX HE VOL INCREASE _   ***.****  CC  (**.***%)
FINAL DENSITY OF HE _      *.****  G/CC
RDX STRAIN ENERGY ___    ***.****  JOULES ___  ***.****  CAL
CUM HEAT LOSS BY HE __   ***.****  JOULES ___  ***.****  CAL
TEMP RISE IN STEEL ___   ***.****  DEG K  ___
THERMAL FLUX INTO RDX AT TIME  ***.** MS  ___  ........... CAL/SQ CM/S

      SKIP 1 LINE
      IF FLAGUHE=1
          PRINT 5 LINES WITH 1000*TIMEU
          THUS
TEMP DIST IN GRENADE AT TIME ***.*** MS

________________________________________
HE  RADIAL       TEMP INCR      LOCATION
LOC (CM)         (DEG K)        INDEX

________________________________________
          FOR I=1 TO NHE DO
              LET J=I-1
              LET R=DRHE*J
              PRINT 1 LINE WITH R,UHEV(I),I
              THUS
 **.****          ***.****       **
          LOOP ''OVER HE GRID
          PRINT 4 LINES THUS

________________________________________
WALL RADIAL      TEMP INCR      LOCATION
LOC (CM)         (DEG K)        INDEX

________________________________________
          FOR I=1 TO NST DO
              LET J=I-1
              LET R=DRST*J+RINT
              PRINT 1 LINE WITH R,USTV(I),J+NHE
              THUS
 **.****          ***.****       **
          LOOP ''OVER ST GRID
          PRINT 2 LINES THUS

________________________________________

      ALWAYS
      STOP
  END ''COMPACT
```

```
FUNCTION PRESS (TMD, RHO)
''
''FUNCTION CALCULATES THE TRANSIENT PRESSURE (KPSI) REQUIRED TO YIELD
''HE DENSITY OF RHO (G/CC), WITH A THEORETICAL MAX HE DENSITY OF TMD.
''TRANSIENT PRESS IS THAT APPLIED DURING LOADING OP'NS OF THE M42/M46
''GRENADE.  TMD OF THE HE IS ALSO GIVEN IN G/CC.  THIS FUNCTION IS THE
''INVERSE OF RHOTRANS.  CALCULATION OF THE PRESSURE FROM RHOTRANS IS
''OBTAINED ITERATIVELY VIA A NEWTON-RAPHSON METHOD.
''
    LET ERR=0.0001 ''KPSI TOLERABLE ERROR
    LET PS= 0.8*RHO/(TMD-RHO) ''QUASI-STATIC PRESSURE FOR DENSITY RHO
    LET P1=1.52*PS
    LET P2=1.53*PS
    LET RHO1=RHOTRANS(TMD,P1)
'L1'LET RHO2=RHOTRANS(TMD,P2)
    IF ABS.F(P1-P2) LE ERR
        GO TO L3
    OTHERWISE
    LET P3=P2+(P2-P1)/(RHO2-RHO1)*(RHO-RHO2)
    LET P1=P2
    LET P2=P3
    LET RHO1=RHO2
    GO TO L1
'L3'RETURN WITH P2
END ''FUNCTION PRESS

FUNCTION RHOTRANS (TMD,PRESS)
''
''FUNCTION CALCULATES AVERAGE DENSITY OF THE HE WITHIN A GRENADE BODY
''FOR TRANSIENT LOADING CONDITIONS.  ARGS:  TMD IS THE THEORETICAL
''MAX DENSITY OF HE IN G/CC, AND PRESS IS THE PEAK PRESSURE IN KPSI.
''PRESSURE GRADIENT WITHIN THE HE IS GIVEN BY THE COEF GRAD.PRS.
''
    LET B=GRAD.PRS*PRESS
    LET ARG=(PRESS+0.8-B)/(PRESS+0.8)
    LET NORMRHO=1.0+0.8/B*LOG.E.F(ARG)
    RETURN WITH TMD*NORMRHO
END ''FUNCTION RHOTRANS
```

```
FUNCTION STRN.ENER (PINT,POUT)
''
''FUNCTION CALCULATES THE HOOP STRAIN ENERGY IN A CYLINDRICAL SLEEVE,
''GIVEN INTERNAL PRESSURE PINT AND OUTSIDE PRESSURE POUT.  SLEEVE
''HEIGHT, INTERNAL RADIUS, EXTERNAL RADIUS, AND YOUNG'S MODULUS FOR
''THE SLEEVE MATERIAL ARE TRANSMITTED AS GLOBAL VARIABLES.  INPUT
''ARGS ARE GIVEN IN PASCALS.  HOOP-STRAIN ENERGY IS GIVEN IN JOULES.
''RESULT IS BASED ON THE LAME EQ'N FOR THICK-WALLED CYLINDERS.
''
    LET A=0.01*RINT
    LET B=0.01*ROUT
    LET L=0.01*LBODY
    LET DENOM=B**2-A**2
    LET T1=A**2*B**2*(PINT-POUT)**2/2.0/DENOM
    LET T2=(PINT*A**2-POUT*B**2)**2/DENOM
    LET T3=2.0*A**2*B**2*(PINT-POUT)*(PINT*A**2-POUT*B**2)*LOG.E.F(B/A)
    /DENOM/DENOM
    RETURN WITH PI.C*L*(T1+T2+T3)/EYOUNG
END ''STRN.ENER
```

```
ROUTINE STRS.STRAIN GIVEN PINT,POUT YIELDING SIGPA,HSTRAIN
''
''CALCULATES MAX HOOP STRESS AND HOOP STRAIN IN A CYLINDRICAL SLEEVE,
''GIVEN INTERNAL PRESSURE PINT AND OUTSIDE PRESSURE POUT.  THE SLEEVE
''INTERNAL RADIUS, EXTERNAL RADIUS, AND YOUNG'S MODULUS FOR SLEEVE
''MATERIAL ARE TRANSMITTED AS GLOBAL VARIABLES.  THE LAME EQUATION FOR
''THICK-WALLED CYLINDERS IS EVALUATED AT THE INT RADIUS.  DIMENSIONS
''ARE GIVEN IN CM.  THEY ARE CONVERTED TO METERS.  MAX STRESS (SIGPA)
''IS GIVEN IN PASCALS.  REF: TIMOSHENKO AND GOODIER, THEORY OF
''ELASTICITY, C. 1951.
''
    LET A=0.01*RINT
    LET B=0.01*ROUT
    LET DENOM=B**2-A**2
    LET SIGPA=(PINT*(A**2+B**2)-2.0*B**2*POUT)/DENOM
    LET HSTRAIN=SIGPA/EYOUNG
    RETURN
END ''STRS.STRAIN
```

```
FUNCTION ESTRN.RDX (PINT)
''
''CALCULATES THE ELASTIC STRAIN ENERGY (JOULES) AS A FUNCTION OF PINT,
''THE PRESSURE (PA) ON THE HE .  A LOCAL HYDROSTATIC STATE IS
''ASSUMED.  VOLUME OF RDX CRYSTALS (VOL.RDX), AND VALUES OF YOUNG'S
''MODULUS (EY.RDX) AND BULK MODULUS (BM.RDX) FOR RDX ARE GLOBAL
''INPUT ARGUMENTS.  RDX VOLUME IS TREATED AS A CONSTANT.  A CONSTANT
''PRESSURE GRADIENT IS ASSUMED WITHIN THE HE VOLUME.  PRESSURE VARIES
''LINEARLY FROM A MAX OF PINT TO A MIN OF (PINT - GRAD.PRS*PINT).  THE
''VALUE OF GRAD.PRS IS ASSIGNED IN THE MAIN PROGRAM AND TRANSMITTED
''GLOBALLY.
''  LET EPS.RDX=PINT/EY.RDX
    LET COEF=1.0-GRAD.PRS+GRAD.PRS**2/3.0
    LET EE.RDX=0.0000005*VOL.RDX/BM.RDX*PINT**2*COEF
    RETURN WITH EE.RDX
END ''FUNCTION ESTRN.RDX
```

```
FUNCTION RPSPEED (XP)
''
''CALCULATES THE RECRIPROCAL PUNCH SPEED IN S/CM AS A FUNCTION OF
''PUNCH DISPLACEMENT XP, IN CM.  INITIAL, CONSTANT ACCELERATION OVER
''TRAVEL XCEL IS ASSUMED.  A FINAL, CONSTANT DECELERATION IS ASSUMED
''OVER TRAVEL:  XPMAX - DCEL TO XPMAX.  SPEED IS CONSTANT WITHIN THE
''RANGE:  XCEL TO XPMAX - DCEL.  XPMAX IS A GLOBAL VARIABLE.
''
    LET MAXSPEED=2.6 ''CM/S
    LET XCEL=0.02 ''CM
    LET DCEL=0.08 ''CM
    IF XP LE 0.0
        GO TO L1
    OTHERWISE
    IF FLAGU=1
        RETURN WITH 1.0/MAXSPEED
    OTHERWISE
    IF XP < XCEL
        LET SPEED=MAXSPEED*SQRT.F(XP/XCEL)
        RETURN WITH 1.0/SPEED
    OTHERWISE
    IF XP > XPMAX-DCEL
        LET SPEED=MAXSPEED*(1.0-SQRT.F((XP-XPMAX+DCEL)/DCEL))
        RETURN WITH 1.0/MAX.F(SPEED,0.1)
    OTHERWISE
    RETURN WITH 1.0/MAXSPEED
'L1'PRINT 1 LINE WITH XP THUS
ERROR.  PUNCH DISPLACEMENT IS OUT OF RANGE:  XP = ............
    STOP
END ''FUNCTION RPSPEED
```

ANNEX B

AMSMC-RDA-S

28 Aug 1985
Revised 24 Sep 85

MEMORANDUM FOR RECORD

SUBJECT: Predicted Bulk Densities of Comp A-5 and Comp A-4 As Functions of Peak Consolidation Pressure

1. Reference:

a. Information Paper, SMCAR-ESM-M, 25 Ap 85, subject: Follow-up Questions on Comp A-5 Density.

b. Ltr, SMCHO-QA, 2 July 85, subject: Density Measurements.

c. Information Paper, SMCAR-ESM-M, 6 Aug 85, subject: Results from Comp A-5 Density Experiment.

d. MFR, AMSMC-RDA-S, 9 Aug 85, subject: Some Observations About the Explosive Sensitivity of Comp A-5.

e. MFR, DRSMC-SAS (R), 4 Nov 83, subject: Particle-Size Distribution of Nominal Class 1 RDX Before Incorporation and After Extraction From Extrusions of Comp C-4.

2. Background

In the Ref 1a paper SMCAR-ESM-M referenced some experimental results of consolidation of explosive Comp A-5 under quasi-static conditions. The applied pressure was permitted to remain at max value for several minutes in this quasi-static test, so that the explosive might be expected to exhibit hydrostatic behavior. The bulk density is given at several values of the peak consolidation pressure. The source of these data is indicated as George Ziegler, SMCAR-LCE. At the time these experiments were run the RDX granulation used in Comp A-5 was much coarser than it currently is. Consequently, there was some concern that the relationship between peak pressure and bulk density might be somewhat different now, using nominal Class 1 RDX, than it was then. Bill Fortune (SMCAR-ESM-M) directed Holston AAP to perform another set of quasi-static experiments on Comp A-5, having the current (nominal Class 1) granulation of RDX and, incidentally, reduced residual solvent level. I suggested a set of pressures at which these experiments were to be run. The range of pressure--7 to 60 kpsi--was greater than the range of Ziegler's data, with some matching pressure values. The results of the tests at Holston were transmitted in Ref 1b. These results are in good agreement with Ziegler's, as shown in Table 1. The average intra-batch standard deviation in the HSAAP data is 0.005 g/ml. An analytic model of the quasi-static, pressure-density relationship is also shown, for comparison.

TABLE 1

COMPARISON OF COMP A-5 BULK DENSITY VERSUS PEAK QUASI-STATIC CONSOLIDATION PRESSURE

Entries are average density in g/ml.

Pressure (kpsi)	Data Source ARDC Ziegler	Holston AAP 7/2/85 *	Calculated **
7	1.61	1.599	1.597
10	1.65	1.633	1.648
15	1.69	1.686	1.690
17	1.70	1.692	1.700
24	1.72	1.725	1.722

* Average of 3 batches of 5 samples per batch.

** density/TMD = $p/(p + 0.8)$, where the theoretical max density (TMD) is 1.78 g/ml.

3. Effect of RDX Particle Size

The tabulated results support the assertion that the initial size of the RDX grains in Comp A-5 (within limits) does not have a measurable effect on the bulk density, obtained under quasi-static conditions. Ref 1c also compares these experiments, but draws a stronger conclusion from them than the conclusion which I have made. In pgf 4 of Ref 1c one finds: "The conclusion then is that there appears to be no physical change to the explosive from the process changes." In view of the fact that bulk density is the only (!) physical quantity being measured here, it may be premature to make this assertion. In fact, evidence cited in Ref 1d indicates that grain size does affect explosive sensitivity in pressed, granular explosives. Further, at the range of density to which Comp A-5 is pressed in the M42/M46 grenade, there is indirect evidence (from tests on similar explosives) that grain fracture occurs during consolidation of these grenades. There is evidence (Ref 1e) of RDX grain fracture when Comp C-4 is extruded at pressures much lower than the 25 kpsi used on Comp A-5. Whether the change in explosive sensitivity due to different initial grain size is important is another issue. The fact is that the results in Table 1 do not address that issue.

4. Average Bulk Density of Comp A-5 After Transient Pressurization

As indicated in Ref 1c, the average bulk density of Comp A-5 under the transient conditions of loading in the M42/M46 grenade is less than the quasi-static value, given the same peak pressure. This fact is conjectured to result from a non-hydrostatic behavior of the explosive during the brief (120 millisec) time the pressure is at or near peak value. A gradient in pressure within the explosive would cause a corresponding gradient in density, yielding a smaller mean value. The compressibility of the explosive (locally) is given to a very good approximation by the quasi-static result:

rho/TMD = p/(p + 0.8), (1)

where the bulk density, rho, and TMD are given in, say, g/ml and where the peak consolidation pressure, p, is given in kpsi. For Comp A-5 the TMD is, practically, 1.78 g/ml. Now suppose that the max pressure reached in the explosive was not the same everywhere within the explosive volume. Specifically, as an approximation, assume a constant gradient of pressure with respect to volume, plotted from the max value on the punch face, where the hydrostatic value, pmax, should occur. Thus, the local pressure-volume relationship would have the form:

p = pmax - b x, (2)

with

b = pmax - pmin,

and where x is the non-dimensional volume coordinate, which varies from 0 to 1 over the volume.
To find the average bulk density (over the grenade internal volume), one must integrate the local density--a function of local pressure--over this volume. This corresponds to substituting equation (2) into (1), and integrating over the non-dimensional volume coordinate x. Formally, let the volume-average bulk density be denoted by E(rho). Then,

E(rho)/TMD = x-integral over (0,1) of :
(pmax - b x)/(pmax + 0.8 - b x) dx. (3)

The result of this operation is a function with one arbitrary constant, b:

E(rho)/TMD = 1 + (0.8/b)ln((pmax+0.8-b)/(pmax+0.8)). (4)

In the limit when b approaches zero, equation (1) is produced, as expected. By examining the (Ref 1c) KSAAP experiments, it is found that a good fit to all results obtains when

b = 0.8 pmax, (5)

for values of pmax from 18 to 29 kpsi. With the above value of b substituted in equation (4), one has the following equation for average bulk density versus peak consolidation pressure.

E(rho)/TMD = 1 + (1/pmax)ln((0.2pmax+0.8)/(pmax+0.8)) . (6)

5. Comparison of Experimental and Calculated Avg Bulk Density

Experimental (transient) average bulk density values, obtained in the KSAAP M42/M46 transient loading tests, were read from a graph provided in Ref 1c. A limited number of transient data points from MAAAP is also shown in Ref 1c. These data are compared (Table 2) with the calculated values of equation (6). The fit over the range appears to be within experimental error. Further, no trend in the residuals is apparent. On this basis one can assert that Comp A-5 falls far short of being an ideal fluid during transient consolidation. A portion of the explosive volume may experience an effective pressure which is only 20 % of pmax in terms of its compressible response.

TABLE 2

COMPARISON OF EXPERIMENTAL AND THEORETICAL AVERAGE BULK DENSITIES OF COMP A-5 AFTER M42/M46 GRENADE LOADING

Peak Pressure (kpsi)	Average Density (g/ml) Exp (KSAAP) VE 81/82	Exp (MAAAP) July 1985	Calculated Transient	Quasi-static *
8		1.500	1.491	1.618
12		1.550	1.574	1.669
14		1.600	1.600	1.684
18	1.640		1.636	1.704
19	1.645		1.643	1.708
20	1.642		1.649	1.712
21	1.657		1.655	1.715
22	1.666		1.660	1.718
23	1.667	1.650	1.665	1.720
24	1.675		1.670	1.722
25	1.676		1.674	1.725
26	1.679		1.678	1.727
27	1.682		1.681	1.729
28	1.685		1.684	1.730
29	1.694		1.687	1.732
30			1.690	1.734

* The quasi-static value, $1.78p/(p + 0.8)$, is offered for comparison.

6. Quasi-static Bulk Density of Comp A-4

It is noted that equation (1), which is used to calculate the quasi-static density of Comp A-5, is written in a non-dimensional form. Both sides of this equation are ratios of dimensional quantities. The only dimensional parameter which relates to compressibility of the explosive is the constant 0.8 kpsi. If this constant is essentially the same for Comp A-5 and Comp A-4, the quasi-static bulk density of Comp A-4 can be calculated from (1) using the TMD = 1.76 g/ml. This density is based on a formulation of Comp A-4 that has an addition of 3.0 % wax to RDX. The assumed density of wax is 0.91 to 0.92 g/ml. Since the formulation of Comp A-4 may vary slightly in percent wax, one should recalculate the TMD if the actual formulation is much different from that assumed. Variation in the TMD of A-4 is also contributed by different waxes. The bulk density values for Comp A-4 shown in Table 3. Comparable values of Comp A-5 are shown for comparison.

TABLE 3

COMPARISON OF BULK DENSITIES OF COMP A-5 AND COMP A-4
VERSUS PEAK QUASI-STATIC CONSOLIDATION PRESSURE

Entries are calculated bulk densities in g/ml.

Pressure (kpsi)	Explosive Composition A-5	A-4 with TMD of: 1.760	1.770
7	1.597	1.578	1.588
8	1.618	1.599	1.609
9	1.635	1.616	1.626
10	1.648	1.628	1.639
15	1.690	1.670	1.680
17	1.700	1.680	1.690
20	1.712	1.692	1.702
24	1.722	1.702	1.713
40	1.745	1.724	1.735
60	1.757	1.736	1.747

7. Conclusions and Recommendations

Mathematical models for the bulk density of Comp A-5 and Comp A-4 have been presented here. Under quasi-static pressurization the equation which relates bulk density to peak pressure has a very simple form. However, this result is shown to match experimental values of bulk density for Comp A-5 over the range of pressure from 7 kpsi to 60 kpsi. When the loading condition on the explosive is rather transient, with near-peak load persisting for only 120 milliseconds, the explosive does not have time to react in a hydrostatic manner. It has been shown that the average bulk density of the explosive in M42/M46 grenades is significantly lower than the quasi-static value obtained for a given pressure. A formula for the average bulk density, after transient loading, is derived here. This formula fits experimental results over the entire experimental pressure range for Comp A-5. A similar formula may be derived for Comp A-4, given some information about the nature of the pressure gradient which exists within the explosive during pressurization. Of course, the same assumption could be made for Comp A-4 as was made for Comp A-5. I have been reluctant to do this, since there is a large disparity in the portion binder in these two explosives. Comp A-5 has about half as much binder as Comp A-4. In the quasi-static case, the compressible behavior of these explosives is predicted to be much the same, relative to their respective TMDs. In the interest of expanding engineering knowledge, it is recommended that: (a) the bulk density predictions of Table 3 for Comp A-4 be verified empirically (as was done for Comp A-5), after quasi-static loading, and (b) the average density of explosive in M42 grenades be measured after transient loading using Comp A-4. Resources permitting, it would also be desirable to measure the local bulk density within the HE in M42 grenades at several locations. These data would support the assumption that the

TABLE 3

COMPARISON OF BULK DENSITIES OF COMP A-5 AND COMP A-4 VERSUS PEAK QUASI-STATIC CONSOLIDATION PRESSURE

Entries are calculated bulk densities in g/ml.

Pressure (kpsi)	Explosive Composition A-5	A-4 with TMD of: 1.760	1.770
7	1.597	1.578	1.588
8	1.618	1.599	1.609
9	1.635	1.616	1.626
10	1.648	1.628	1.639
15	1.690	1.670	1.680
17	1.700	1.680	1.690
20	1.712	1.692	1.702
24	1.722	1.702	1.713
40	1.745	1.724	1.735
60	1.757	1.736	1.747

7. Conclusions and Recommendations

Mathematical models for the bulk density of Comp A-5 and Comp A-4 have been presented here. Under quasi-static pressurization the equation which relates bulk density to peak pressure has a very simple form. However, this result is shown to match experimental values of bulk density for Comp A-5 over the range of pressure from 7 kpsi to 60 kpsi. When the loading condition on the explosive is rather transient, with near-peak load persisting for only 120 milliseconds, the explosive does not have time to react in a hydrostatic manner. It has been shown that the average bulk density of the explosive in M42/M46 grenades is significantly lower than the quasi-static value obtained for a given pressure. A formula for the average bulk density, after transient loading, is derived here. This formula fits experimental results over the entire experimental pressure range for Comp A-5. A similar formula may be derived for Comp A-4, given some information about the nature of the pressure gradient which exists within the explosive during pressurization. Of course, the same assumption could be made for Comp A-4 as was made for Comp A-5. I have been reluctant to do this, since there is a large disparity in the portion binder in these two explosives. Comp A-5 has about half as much binder as Comp A-4. In the quasi-static case, the compressible behavior of these explosives is predicted to be much the same, relative to their respective TMDs. In the interest of expanding engineering knowledge, it is recommended that: (a) the bulk density predictions of Table 3 for Comp A-4 be verified empirically (as was done for Comp A-5), after quasi-static loading, and (b) the average density of explosive in M42 grenades be measured after transient loading using Comp A-4. Resources permitting, it would also be desirable to measure the local bulk density within the HE in M42 grenades at several locations. These data would support the assumption that the effective pressure exhibits a constant gradient within the HE volume. Local densities should be measured at three locations on the grenade axis, from the cone to the inside of the cap (dome). Also, at a midaxial station, three local radial positions should be sampled for bulk density at different polar angles.

George Schlenker

GEORGE SCHLENKER

Operations Research Analyst

AMSMC-RDA-S